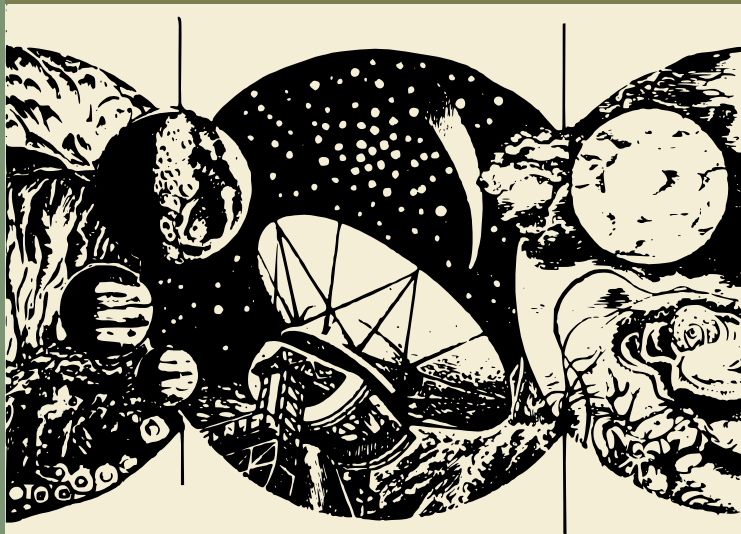


# Radar Made Easy

Mir Publishers

Moscow



M. Razmakhnin





М. К. Размахнин  
РАДИОЛОКАЦИЯ  
БЕЗ ФОРМУЛ,  
НО С КАРТИНКАМИ

Издательство  
«Советское радио»  
Москва

# **Radar Made Easy**

**M. RAZMAKHNIN**

Translated from the Russian by  
**B. KUZNETSOV**

**Mir Publishers  
Moscow**

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# Foreword

By tradition, an author writes a foreword to explain what his brain-child is like, what material has been used, and who is expected to read it, and how. He is also supposed to thank as many people as he can, including those he is going to confront. In this way he hopes to chain them up to his writing chariot and to forestall their criticism reliably.

Since a foreword is a deep-rooted tradition in the publishing trade, one must write it, no matter how one feels about it. Yet a conventional foreword, as this author thinks, would be out of place in a book like this. So his choice has been a kind of dialogue in which one side will be hereafter referred to as **AUTHOR**, and the other side, a person acting on the strength of the publishing code, will go under the clandestine name of **PUBLISHER**.

So the **PUBLISHER** strikes first.

*P.* What sort of book we shall call it according to the formal classification of literary works?

*A.* To be frank, I find it hard to place my book precisely. The point is that it is in two widely differing parts. The first is more in the nature of scientific advertising, and the second approaches closely popular science, although it has been strongly influenced by

“science for fun” books now in vogue, like J. Williams’ *The Compleat Strategyst* and Ya. Khurgin’s *So What?*

P. To put it another way, your book does not belong to any form of literary work officially established.

A. Well, then let’s call it popular science.

P. What material have you used?

A. Mostly periodicals, and some books.

P. Whom is the book intended for?

A. The “enlightened layman”, a man with a good educational background and knowing about the subject-matter only what he can learn through the mass media (radio, television, the press, etc.). This book is decidedly for him. And, of course, for school graduates and any one interested in radar. It is not unlikely that radar specialists too will leaf through it. Of course, they will be attracted not so much by the subject-matter as by the drawings made by E. Treskin. They deserve it.

P. How should your book be read? The question may sound strange, but there are books in which the authors suggest the reader read first, say, chapters 1, 2, 4, 7, and 3, then chapter 6, then chapter 1 again.

A. The text may be read in normal sequence, and the drawings from beginning to end or the other way round.

P. May your book serve as a study aid?

A. Positively not, for all the author’s effort to present some chapters as they would be in a text-book. In fact, some chapters contain problems for the reader to work out on his own, but nothing will happen if he chooses not to. The succeeding chapters will be easy to understand anyway. The more elaborate situations are numbered and discussed in that order. The author has made it a point to note both merits and demerits of all the methods and techniques discussed. In this, the author has tried to be objective. Still, the book cannot be

used as a study aid. It will leave a layman a layman as regards radar, although it may stimulate his interest in the subject. That is the author's ultimate goal.

*P.* Is there any one you would like to thank for assistance?

*A.* Yes, of course. Above all, the people who have worked on the manuscript, for their practically unrewarded effort.

And last but not least. Since this is a popular-science book, the author may well have distorted the true picture in his effort to present not uncommon things in simple form. I apologize in advance to the meticulous reader who will spot some inaccuracies.

## By Way of Explanation

The reader has the right to be intrigued or at least led to take interest in a book. Otherwise, with his constant lack of time for leisure, he will hardly try and read a single page in a book he had heard nothing about. The author is forced, therefore, to envy the writers of text-books, for even an ordinary manual nowadays can well compete with classics and best-sellers among detective stories in the number of copies printed and of readers won. And what readers! The young and middle-aged people who have learned to be stingy with their time and are especially exacting as far as books go.

Well, let us begin with a puzzle. What you have before you on the opposite side is a page from a book. What book do you think it is?

The puzzle may seem simple to guess. Of course, you may think, this is a page from a book on mathematics or at least a treatise on pure physics. If you think so, you are wrong, or partly wrong, to be correct. Naturally, it has to deal with mathematics, but this would be also true of any present-day special book. Its title is *Theoretical Principles of Statistical Radar*. Now you've run into the word our book has in its title. Radar is a field of radio and electronics where a description of

$$\hat{\lambda}_n = \sum_{i=-N}^n \tilde{\Lambda}_n^{(i)} \sum_{k=1}^n C_{(i)k} [z_{(i)k} + K_{(i)k} (\hat{\lambda}_k + \Delta_{(i)k} - \bar{\lambda}_k)] + \bar{\lambda}_n, \quad (6.6.78)$$

$$C_{(i)} = [A_{(i)} + V]^{-1}; \quad \tilde{\Lambda}_n^{(i)} = \frac{\Lambda_n^{(i)}}{\sum_{k=-N}^N \Lambda_n^{(k)}},$$

$$\begin{aligned} \Lambda_n^{(i)} &= P(y | \hat{\lambda} + \Delta_{(i)}) \left[ \frac{\det(A_{(i)}^{-1} + R)}{\det A_{(i)}^{-1}} \right]^{-1/2} \times \\ &\times \frac{\exp \left\{ -\frac{1}{2} [z_{(i)} + A_{(i)} (\hat{\lambda} - \Delta_{(i)} - \bar{\lambda})] + (A_{(i)}^{-1} - C_{(i)}) [z_{(i)} + A_{(i)} (\hat{\lambda} - \Delta_{(i)} - \bar{\lambda})] \right\}}{\exp \left\{ -\frac{1}{2} z_{(i)}^+ A_{(i)}^{-1} z_{(i)} \right\}} = \\ &= P(y | \hat{\lambda} + \Delta_{(i)}) \frac{P_{\varepsilon w(i)}}{P_{w(i)}}. \end{aligned} \quad (6.6.79)$$

$$\begin{aligned} \hat{\lambda}(t) &= \sum_{i=-N}^N \tilde{\Lambda}^{(i)}(t) \int_{t_0}^t c_{(i)}(t, \tau) [z_{(i)}(\tau) + K_{(i)}(\tau) (\hat{\lambda}(\tau) - \Delta_{(i)}(\tau) - \\ &\quad - \bar{\lambda}(\tau))] d\tau + \bar{\lambda}(t). \end{aligned} \quad (6.6.80)$$

$$\tilde{\Lambda}^{(i)}(t) = \Lambda^{(i)}(t) / \sum_{k=-N}^N \Lambda^{(k)}(t);$$

$$\begin{aligned} \Lambda^{(i)}(t) &= P(y(t) | \hat{\lambda}(t) + \Delta_{(i)}) \exp \left\{ \frac{1}{2} \int_{t_0}^t K_{(i)}(\tau) z_{(i)}^2(\tau) d\tau - \right. \\ &\quad \left. - \frac{1}{2} \int_{t_0}^t K_{(i)}(\tau) [z_{(i)}(\tau) + K_{(i)}(\tau) (\hat{\lambda}(\tau) - \Delta_{(i)}(\tau) - \right. \\ &\quad \left. + \frac{1}{2} \int_{t_0}^t c_{(i)}(t, \tau) [z_{(i)}(t) + K_{(i)}(t) (\hat{\lambda}(t) - \Delta_{(i)}(t) - \right. \\ &\quad \left. + K_{(i)}(\tau) (\hat{\lambda}(\tau) - \Delta_{(i)}(\tau) - \bar{\lambda}(t))] dt d\tau + \right. \end{aligned}$$



underlying principles involves the use of mathematics well beyond the depth of people with university education. In contrast to pure mathematics or pure physics, however, we run into radar literally everywhere. Also, the number of people busy with the theory of radar, radar engineering, and operation of radar exceeds by far the number of pure mathematicians and physicists.

Now, it is the right time to explain why this book has been written and what the reader can trade his time for. Naturally, this book is not for radar specialists, nor is it a manual on radar. Rather, it is an attempt to explain in simple terms what radar is like, what it does, why it is so important to the present-day world, and why a huge army of enthusiasts have made it the goal of their lives.

Since we do not count on specialist readers, we shall try and use no mathematical formulas (the page shown as a puzzle does not count). We shall explain things "with fingers", as it were. As an aid to this ancient device, we shall use pictures, for, as a proverb goes, to see once is better than to hear a hundred times (maybe, a hundred times is too much, but as a figure of speech it will do). Indeed, a single picture carries more information than a text occupying the same space. As a proof, try to describe in detail what you can see in any of the pictures in the book and estimate the space it would take to hold your description set up in the smallest type. So . . .

# Part One Making an Acquaintance



## WHAT IS RADIOLOCATION?

Almost certainly, this question will not embarrass the reader. Not that he is busy with radiolocation — simply he has read and seen a good deal from magazines, TV programs, popular-science films and newsreels about the spinning radar aerials and the concentrated faces of radar operators as they watch what they call “target pips” — intriguing light spots on the faintly luminous radar scopes. That much is familiar to one and all. Now we are going to take a deeper sight into the matter.

It is appropriate to begin with a definition. From any published authority you will learn that “radiolocation is the use of radio waves to detect an object or to determine its direction, position, or motion in air, on water and land”.

Everything is clear — as far as it goes. In case it does not go far, a few explanations are in order.

To begin with, a radio wave is emitted into the surrounding space (this job is done by a transmitter), and the arrival of a return signal is waited for. Its arrival is announced by a radar receiver operating in company with a huge aerial capable of picking up faint signals. Nothing will come back if there are no objects around the transmitter to reflect the emitted radio waves. In

all probability, however, the radio waves will run into anything on their way out. Then they will either be reflected or scattered. With reflection, the part of the wave striking the reflecting object retains its shape but is caused to travel back. As radar specialists say, a specular reflection has taken place. When picked up by the aerial, the reflected wave gives rise to a fairly strong signal in the receiver — the larger the area of the reflecting object, the stronger the received signal and the brighter the pip on the scope. Unfortunately, the reflecting surface may be so positioned that the reflected wave will be sent back away from the aerial, and no reflected signal will reach the aerial.

This can readily be modelled at home. Take a small mirror and wait for the sun to appear in your window. The sun will act as a radar transmitter, and as a receiver for the reflected signal you may well use, say, a cat. So long as the reflection of sunrays is playing on the wall, the cat will be sitting quietly (there is no reflected signal to strike the receiver). As soon as the reflection strikes the cat it will close its eyes — it has picked up the reflected signal. True, that will be the end of the experiment. The cat will run and stay away from you for a week or so. Yet, the truth has been proved, and science may triumph. To avoid all trouble, however, make this experiment mentally. It will be no less convincing.

Now about scattering. A scattering object may be visualized as consisting of a multitude of tiny mirrors facing in all directions. The reflected signals will travel in all directions, too, but each will be extremely faint. One, or even some, of them will inevitably strike the aerial, and the receiver will register the presence of a reflecting object, or target (as it is called in radar parlance). For this to happen, the receiver must be a highly sensitive one.

So far we have had in mind only the geometry of targets. Their physical properties, however, are as important to the magnitude of the reflected signal. The best reflectors are metal objects and generally all materials conducting electricity well. They will absorb only a tiny portion of the incident wave, and the reflected signal will carry about as much energy as the transmitted signal. Other materials absorb radio waves eagerly, and their reflections are weaker. Yet, any obstacle on the way of radio waves will reflect some of their energy. Even clouds, no matter how ethereal they may look, will produce a pip on sensitive radar scopes.

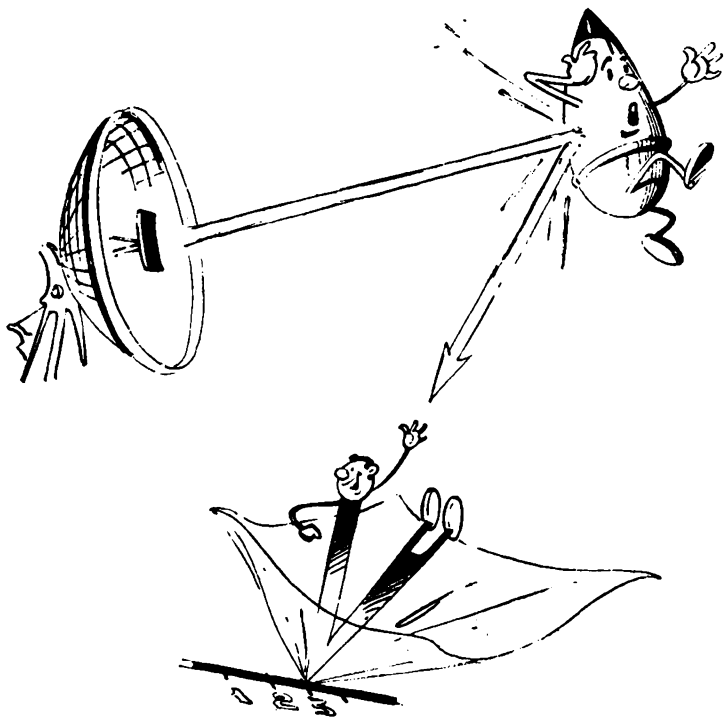
Now we have learned that for radiolocation we need a transmitter, an aerial, a sensitive receiver, a signal, and a reflecting object. What we do not know yet is how to make them cooperate. This can be arranged in a variety of ways, and with each arrangement a radar station will operate differently. We shall take up two basic types of radiolocation, or radar, as it has come to be known.

A pulsed radar emits radio waves as bursts of short radio pulses each with a duration of a few thousandths or millionths of a second. Just as the transmitter sends out a pulse, the receiver is turned off, lest the strong transmitted pulse should damage it. Just as the transmitter ceases emitting, the receiver is turned on and waits for the weak reflected signal to come back. Some time later, after the reflected signal has come back or all hope has been lost that one will arrive, the transmitter is turned on and the receiver is turned off again. These events are repeated all over again so long as a radar is operating.

This type of radar works in much the same way as a person fond of listening to ordinary echoes. You surely know a place where echoes come in best. Go there, shout something out loud, and listen. If you are lucky,

you will hear an echo repeated two or three times. When the echo has died away, shout something once more, and the echo will come in again. If you shout all the time, you will hear nothing, because your voice will mask the echo. So a radar stops emitting in order that weak reflected signals (also called echoes by radar men) can be discerned.

Still, there are radars which emit waves continuously, and they are called continuous-wave (CW) radars. How do they receive echo signals? Radio waves



are electromagnetic oscillations recurring at particular frequencies. Let the transmitted signal be of frequency No. 1. Then the radio echo reflected from a stationary target will come back at the same frequency No. 1. When reflection is from a moving target, the echo signal will have a different frequency. If the target is approaching the radar, the frequency will rise; if the target is receding from the radar, the frequency will go down. At audio frequencies, this effect\* can be noted by listening to the whistle of a passing-by train. When the train is approaching you, you will hear a high-pitch tone; when the train is receding from you, the pitch will go down. This example is given in any school book on physics, and you surely know it.

The receiver of a CW radar is tuned so that it will not pick up the transmitted frequency at all. But it will receive any frequencies above or below the original one. This is why a CW radar cannot "see" stationary objects — their echoes are of the same frequency as the transmitted one. On the other hand, it will miss not a single moving object, and its pips will be displayed on the scope. Unfortunately, Doppler radars (as they are usually called) cannot determine the distance (or range) to the targets.

There are CW radars using more elaborate techniques of transmission and reception, which can determine target range, too. In these radars, the transmitter frequency is varied, or modulated, continually, and they are called frequency-modulated (FM) radars. By way of example, an FM radar will emit frequency No. 1 during the first time interval, frequency No. 2 during the second, frequency No. 3 during the third, etc., so that during the tenth time interval it will emit frequ-

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\* This is called the Doppler effect after the scientist

who first observed and described it.

ency No 10. During the eleventh time interval it will again emit frequency No. 1, and the sequence of frequencies will then repeat itself. The receiver is capable of picking up signals on all the frequencies except the one used at a given instant. Now imagine that while the transmitter is emitting frequency No. 6, the receiver picks up frequency No. 2 used during the second time interval. It is not hard to calculate that the signal has completed the round trip in four time intervals. From the velocity of radio-wave propagation (it is the same as that of light) and the time elapsed, we can readily find the distance travelled by the waves. Dividing this distance by two will give the range to the target. This type of radar can see both stationary and moving targets. True, a correction for the Doppler effect has to be applied for moving objects (we shall leave out these niceties for the time being, however).

For all the multitude of radars now in use and for all the diversity of functions they perform and the arrangements they use, the radars can be grouped into the two types we have just discussed.

A few remarks are in order concerning the succeeding chapters. Part One will describe where and how the various radars are used; Part Two will be concerned with the operation of present-day radar in greater detail. That will be later on, and now we shall learn how radar has come to be used by the military.

## RADAR'S WAY INTO THE ARMED FORCES

Radiolocation was born into a scientific family, and it spent its childhood with peace-loving science workers. Indeed, A. Popov's early experiments with reflections of radio waves from ships had nothing to do with war. The military seem to have been indifferent

to radiolocation at that time; anyway there are no records to the contrary.

The earliest known precursor of radar, the ionospheric sounding station built under M. Bonch-Bruевич in the Soviet Union in 1931, was likewise a non-military equipment for studies into the ionosphere, the outer part of the Earth's atmosphere. But while scientists were busy in the quiet of their labs, a veritable technological revolution started in the leading armies of the world. The military had realized that scientific discoveries could help to win battles or even wars, and radiolocation in company with other scientific and technological discoveries was enlisted in the armed forces. Aware of the advantages that the unshared use of radiolocation could offer, the military put radar under their almost exclusive control.

To see and not to be seen by the enemy — that was the soldiers' dream of all times. With radar the dream had come very nearly to becoming a reality — at least as long as the enemy had nothing to parry with. Naturally, anything bearing on radar was classified as top secret. In the United Kingdom radar was ranked as the Top Secret Weapon. In the United States documents on radar bore the inscription "Burn After Reading". Fortunately, they did not stick the label "Burn Before Reading". Even though this could ensure complete secrecy, it would stand in the way of progress. Yet, despite all drastic measures, radar advanced at about the same pace in all developed countries. Scientists and engineers in different countries made the same discoveries and came out with the same technical ideas and developments at practically the same time. In the late thirties, radar stations appeared in the Soviet Union, the United States, the United Kingdom, Germany, and France. So, the unshared use of radar was out of the question. In addition to land, air and sea, war was

now to be fought in the ether. In this war, superiority would depend not so much on the number of radar troops as on the qualifications and skills of the engineers working in the deep rear.

So, radar had joined the armed forces. That did radar a lot of good. With lavish support for research from the armed forces and with many enthusiasts of radar among the military, work could now proceed on a larger scale and at a faster pace.

What can radar do for the military? To answer this question, one needs to review where radar is used in the present-day armed forces and how. The author put down this sentence and fell to thinking. There is no simple way to go about it. The military are loath to share information on radar with the press. Items on military radar are a rare occurrence in newspapers or magazines. But even then they carry a most general material or, still worse, have been written for publicity to promote the products of a particular maker and lack in objectivity.

It is a good deal simpler to tell about radar in civil aviation, on railways, or on merchant ships. The more so that the civil radar operates on exactly the same principles as its military counterpart. Small wonder, therefore, that in describing the operation of the radar used for flight control in the Air Force we shall use the set-up of a civil airport, and in the story about marine radar we shall refer to its service with the merchant marine.

Yet, radar today appears to be used in the armed forces on a much larger scale than it is in non-military applications. This is why our classification of radar will be based on its affiliation with a particular service, the Air Force, the Missile Troops, the Navy, and the Army.

The early radar stations adopted by the armed for-

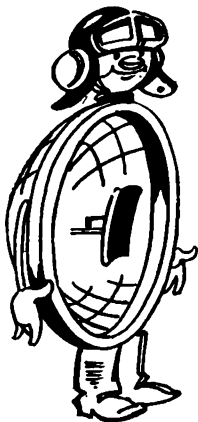
ces were to detect enemy aircraft and were elements of anti-aircraft defence. This was why the Air Force led the other services in terms of "radar equipment per serviceman" until the advent of missile troops. The missile men captured the leading position at once and, apparently, for long. Still, to follow the historical chronology, we shall begin with radar in the Air Force, and aviation in general.

## RADAR AND AVIATION

To fliers, weather men have always been "weather gods". So, it is appropriate to start with what present-day weather gods use — weather radar. It locates clouds and, especially, storm fronts, determines the rate of precipitation, and keeps a constant watch on the origin and propagation of hurricanes and storms. The data thus collected go into weather forecasts circulated at once to all airfields and air traffic control centres.

In recent years, a scheme has been advanced in the United States to collect weather data by air-borne radars. According to American specialists, twenty-two planes continually relaying weather data to a computing centre will be able to report the weather at any point on the globe.

A present-day Air Force air-drome has at least one runway for aircraft to take off from and to land on. To avoid congestion one is forced to use air-traffic control radar. It usually operates in company with a computer and clears aircraft for take-off or



landing. In doing so, the radar-computer complex takes into account flight duration, aircraft priority, the occupancy of the runway, and some other factors. One type of airport surveillance radar can keep watch on the runway and taxitracks and handle up to eighty aircraft an hour coming in for landing or readying to take off. Obviously, this could hardly be done without radar.

In the Soviet Union this job is done by the "UTES" radar system. It can pick up an incoming plane at a distance of hundreds of kilometres and an altitude of several thousand metres and track it as far as the airdrome. Within seconds, the system identifies the plane, takes its azimuth and altitude, and calculates the amount of fuel left on board. For the first time the "UTES" system went operative for air traffic control around Moscow. Its service record to date has been one of high accuracy and reliability.

This type of radar system has capabilities sufficient to cover up to 200 runways at a time. With its centre located at, say, Brussels, such a system would have control of practically all major airports in Western Europe. In this system, signals from all incoming planes are routed to a computer which identifies the planes and compares their actual routes with those stored in its memory. Should a plane depart from its assigned route or should an unauthorized plane intrude in the air space, the system will alert interceptors to take care of the situation.

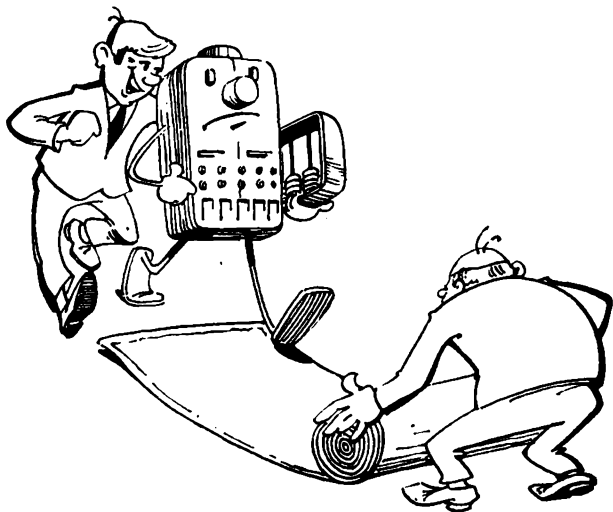
These systems handle planes in flight or approaching an airdrome. At landing, precision-approach radar, PAR for short, takes over. One such system uses two radar beams, one to guide the aircraft onto the centre line of the runway and the other to steer it down along an optimum glide path. Each beam produces a pip on the respective radar scope in front

of the air traffic controller. From these scopes the controller can immediately see when the plane deviates from the right heading or the right glide path and will talk the pilot back on his course. Both the controller and the pilot can be replaced with a computer to notice any departures and to correct them. What we have then is an automatic ground-controlled approach (GCA) system with which planes can land safely in any weather and under any conditions of visibility. Without such a system all-weather fighters and bombers could not operate at all.

The actual combatant among radars, however, is the early-warning radar. An early-warning radar set uses high-power transmitters and huge aërials installed at advanced positions to ensure a longer range of detection. Early-warning radar operates on much the same principle as airport surveillance radar, but its objective is entirely different. While airport surveillance radar ensures safety of flight and landing for as many planes as practicable, early-warning radar is expected to detect and to help destroy as many enemy aircraft as it can.

During World War II, early-warning radars could only detect enemy planes taking off from forward airfields, and friendly fighters had barely enough time to parry the attack. Today, early-warning radars will spot the enemy well before it approaches the defence line, so that a surprise air attack can hardly be successful.

When attacking planes approach the defence line, the early-warning radar hands them over to a fighter-control radar, with the fighters already air-borne. Keeping an eye on the radar scopes to ascertain the position of friendly and enemy planes, the fighter-control officer informs the fighter pilots as to the correct course, speed, and altitude. During World War II, a fighter-control



officer could watch an air battle visually and had enough time to command the fighters. Today, however, with fighters flying at supersonic speeds, the air situation is so complicated and so fluid that the control officer could hardly cope with his task without radar.

A fighter-control radar has a shorter range than an early-warning radar, but it determines the position of an aircraft with a greater accuracy which is important for vectoring (that is, steering) fighters to a target until it falls within the range of a fighter-borne radar.

When this happens, the distance between the fighter and target becomes so small that the two pips almost merge on the scope of the ground-based fighter-control radar, and it cannot do its job effectively any longer. This is why the fighter-borne radar comes in.

As soon as the beam of the fighter-borne radar locks

onto the target, the fighter can approach and attack the target on its own. With all the important fire data (target range and altitude) displayed on the scope, the pilot can engage the target without actually seeing it. What is left for the pilot to do is to choose the right instant and to press the firing button. In some cases, this, too, is done by a computer. Of course, this is not to imply that the pilot has nothing to do at all in an actual air battle — things do not look so simple as they do in our story.

It is a well known fact that a combat plane is especially vulnerable from the rear. In fact, a tail attack has often meant a sure "kill" for the attacker. This is why much has been done to protect the plane's tail. One device is a tail-warning radar capable of detecting enemy planes approaching within a firing distance. Sometimes, this radar can double as an automatic radar sight for the tail defensive system. Then, in closing in on a bomber carrying a tail-warning radar sight, a fighter will invite fire upon itself, which will in no way help with its mission.

Another standard piece of radar equipment on bombers is an all-round looking search radar. It looks round the terrain over which the plane is flying, and its scanning beam paints the ground and everything located on it. Forests, ploughed fields, rivers, and structures reflect the beam differently, and as differently they appear on the scope. The picture on the scope looks like a black-and-white photograph or, rather, plan for which reason this type of display is often called a plan-position indicator. Metal objects, *viz.*, rail tracks, bridges and buildings, stand out best. With such a map, the navigator can readily check his route and select a lucrative target for bombing. An airborne computer will calculate the time for bomb release with allowance for altitude and speed of the aircraft and apply a suitable

mark on the scope. As soon as the target echo lines up with the mark, the bomb release operates, and the lethal load is dropped on the enemy.

The press has more than once carried news items about radar-carrying reconnaissance drones. A ground-based radar keeps them in view and steers them at will. A drone usually carries an all-round looking radar. However, there is nobody on board the drone to watch the picture on the scope, nor is there any scope for that matter. A high-power transmitter relays the echo signals to the friendly troops, and an operator sitting in an underground shelter can see a map of the terrain under the drone, picking last-minute intelligence about the enemy.

In combat, there is always the danger of being fired at by friendly troops inadvertently. As a precaution, soldiers in any army are trained to identify enemy aircraft, tanks and other combat vehicles by their silhouettes.

However the radar scope does not show the silhouette of a plane. How then can it be identified? For this purpose, aircraft carry "identification, friend or foe" (IFF) units each consisting of a receiver and a transmitter. The receiver picks up an interrogating radar pulse from a friendly radar and turns on the IFF transmitter which sends back a signal to distinguish the plane from enemy forces. This IFF signal appears on the scope next to the target echo, as if saying "I'm a friend!" To prevent the enemy from using the same IFF signal frequency, the transmitter uses a code, and the ground receiver is tuned to pick up only that code. Now the receiver will not pass enemy signal onto the indicator, and the operator will be sure the target echo he sees is one from an enemy plane.

Almost all of the radar types mentioned above are used in the national air traffic control system set up in

the United States. The system has a total of some 120 radars at airports to track approaching or transit planes and to control aircraft at take-off and landing, and also a network of en-route radars serving between them twenty-one sectors. This type of radar has a range of about 300 km. Besides, each airport has an air traffic control service of its own, comprising an airport surveillance radar with a range of about 80 km, a weather radar, a long-range radar to measure the distance to incoming planes, and an interrogator to identify the nationality of the aircraft and their altitude.

Of special concern to controllers who have to deal with ever-growing air traffic are small private planes. As a rule, they fly no planned routes or preset schedules. To make the situation still worse, their echoes on radar scopes are very faint, and the controller may well miss them. As a way out, private planes are instructed to carry metal reflectors which make their radar echoes comparable in size and strength with those from big jets. In this way, the air-traffic controller is sure to notice these dangerous targets in time.

We might also mention radio beacons which help planes to determine their bearings or directions relative to their destinations, radio navigation systems, and many other things. We shall discuss them later on.

## RADAR AND MISSILES

The missile troops are the junior service of all, but in terms of radar they have overtaken the Air Force by a good margin and are firmly holding the leading position. Almost everything done by the missilemen is related — in one way or another — to radar. Take, for example, a ballistic missile. Its flight path may be broken into a powered leg when the missile is propelled by

its rocket motor, and a ballistic leg when the motor is no longer burning and the missile follows a trajectory like that of a thrown stone, determined by the magnitude and direction of speed at the instant of throw, and its mass. The ballistic missile can be controlled in its flight as long as its motor supplies thrust. After burn-out, no control is possible. If a ballistic missile is to hit its assigned target, it must have a certain definite velocity and direction at burn-out. In this, a good deal of help comes from the radars set up next to the launching site. They keep a constant watch on the flight path of the missile and generate commands to fire the respective thrusters (or vernier motors), should the actual path differ from the desired one. Thrusters are small engines, but their thrust is sufficient to correct minor departures from the desired speed and direction. Once the missile has arrived at a pre-determined point on the trajectory and attained the right speed, the main motor and the thrusters are turned off, and the final stage of the missile sets out on its journey along a ballistic (or free-flight) curve. The radars may keep watching the flight, but the missile is no longer controllable because the motors have been shut down.

As a rule, ballistic missiles are assigned to strike strategic targets. They are aimed at major or especially important installations which cannot change their location (such as industrial complexes, administrative centres, large ports, missile bases, and the like). Although no longer controllable on its final leg of flight, a ballistic missile is sure to hit its target, provided it has been put on the right trajectory.

The situation is different with smaller anti-aircraft and anti-missile missiles (ones intended to destroy enemy missiles in flight). Their targets travel at a high speed and use manoeuvres to avoid the fatal collision. Now the radars have to keep watch on the missiles

from launch to impact. The flight paths for these missiles are calculated by computers which also send commands through a radar transmitter to adjust course or speed. The radars track the missiles and targets until both pips merge into one, and this bursts into tiny sparklets indicating that the target has been destroyed.

In a book on radar we find a description of an anti-missile complex. The word "complex" has been chosen deliberately. You can assign anti-missile defence to any number of most up-to-date radars, but they may fail to destroy enemy missiles unless they cooperate properly. Whatever is learned by one radar must immediately and unerringly be relayed to all other radars and the defence centre. To cater for these needs, the complex incorporates computers and highly reliable automatic communications links. With them, the individual radar units set up at distances of several hundred or even thousand kilometres from one another can operate as one.

We have mentioned the radars of the anti-missile complex. The first to learn about an enemy attack are the operators of distant early-warning (DEW) radars. While they study the target pips on their scopes, the associated computer determines the present position of the target, plots the most probable flight path, and decides whether the target constitutes a threat. In a matter of seconds, the computer classes the target as a satellite, a meteorite, or an enemy missile. In the latter case, a suitable signal is sent out over the communications links to the defence centre and an acquisition radar. The acquisition radar determines the target coordinates with a greater accuracy and relays the data to an identification radar which verifies the target position and locates the warhead among the decoys dropped by the missile on its final leg of flight.

An idea about the size and complexity of these

radars can be gleaned from these figures. An identification radar in service in the United States weighs 200 tons and uses a parabolic aerial measuring 26 metres across and placed under a radome (to protect it from exposure to wind, rain and snow) 43 metres in diameter. The whole structure stands taller than a 15-storey building. Its cost is estimated at about 16 million dollars. And this is only one unit out of the entire complex.

The three radars we have just mentioned make up a decision-making level. Once they have decided that the target constitutes a threat, a firing element acting as a decision-enforcing level goes into operation. In addition to an anti-missile missile battery, it includes a tracking radar and a guidance radar. The tracking radar follows the target and measures its present coordinates. The guidance radar does the same for the missile. Data from both go to a computer which shapes the requisite flight path for the missile, and the respective commands are relayed over a command radio link to the missile to steer it to impact with the target.

Other systems operate in a somewhat different way. One of them is the Safeguard system, the first complex of which, as American newspapers promise, is to be built by 1974 at Lengdon within 3,500 kilometres of the US-Canadian border. It will consist of two radars and launching sites for interceptor missiles. The search radar developed by the General Electric will be a long-range equipment intended to give an early warning of enemy warheads at a distance of 1,500 kilometres or more and to track them. The radar will be set up in an underground reinforced-concrete blockhouse measuring 60 metres in length and width and 40 metres in height. The remaining facilities of the complex will include an electric-power plant, an approach tunnel, and an underground communications

link. The launching sites will be equipped to fire the long-range "SPARTAN" and short-range "SPRINT" missiles. They will be steered to impact with enemy warheads by the second radar to be used for launching-site defence. It will track targets over distances of several hundred kilometres, identify the most dangerous target, and guide anti-missile missiles to destroy it. These extremely sophisticated and advanced radars are expected to intercept from tens to hundreds of targets at a time. This will be a formidable task, indeed, even for these amazing radars.

They will be amazing in terms of cost, too—each will call for a capital outlay of 150 to 200 million dollars from breaking ground to action tests.

By far the most important element of these systems is the distant early-warning radar. The earlier it detects a target, the more the time available for readying the defences.

In order to detect a target at the earliest possible time one must have a very powerful radar. Such a radar has been built. Yet, a still earlier detection would be better. So, radar specialists are contemplating two approaches to this problem.

One approach is to set up radar pickets. These may be carried by ships or aircraft. A navy radar picket will use many ships sailing in the international waters, a long distance from the home country. The routes for them will be chosen such that they can keep watch on all the likely paths over which enemy missiles can be launched. An airborne radar picket can serve the same purpose, but it has an advantage over a ship-borne one because its detection range increases with altitude, and so it can detect targets at an earlier time. Radar picket aircraft are slow (of course, in comparison with supersonic fighters and missile-carriers), but they can stay airborne for a long time.

The other approach is to use transhorizon radars. Conventional radars operate on microwaves, that is, on waves from one to a hundred centimetres long. These waves are propagated along practically straight lines and cannot bend around the earth's surface. This is the reason why the coverage of these radars is limited by the distance to the horizon (the line-of-sight distance) and this is why the range of airborne radars increases with altitude—as a plane flies higher, the distance to the horizon increases.

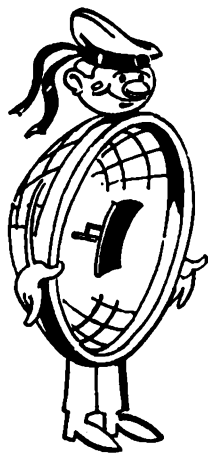
The use of longer waves for radar entails a number of inconveniences. For one thing, targets reflect the longer waves not so well as the shorter ones. For another, radar equipment grows bulky and unwieldy. Still more important, the target position is determined with lesser accuracy. However, the longer waves can follow the curvature of the earth and “peep” beyond the horizon. In the expert opinion, the chief task of distant early-warning radars is to establish the very fact that the enemy has fired a missile. The shaft of flame rising at shoot-off will reflect long waves fairly well, and the receiver will be able to register the echo signal. As to the precise coordinates of the target, they may be determined by other radars closer to the defence line. It is not unlikely that a trans-horizon radar system of the future will be able to spot a missile launching at any place on the earth.

Some of the trans-horizon radars operate on high frequencies (with waves from ten to a hundred metres long). These HF waves cannot bend around the earth's surface, but are reflected from the ionosphere as if from a mirror, and can reach localities far beyond the horizon. Sometimes, an HF wave will skip from earth to ionosphere more than once and will carry the signal all the way round the globe. Then a radar receiver will pick up a signal, of course a very faint

one, which will tell us a good deal about the reflecting power of a long chain of localities girdling the earth.

For a surer "kill", anti-missile and ground-to-surface missiles carry small radars of their own. Once a missile has come within a certain distance of the target, its radar takes over. It both illuminates the target and picks up the echoes, while a built-in logic system steers the missile to impact with the manoeuvring target. Some missiles only carry a radar receiver. Then the target is illuminated by a ground-based radar, and the missile-borne radar receiver only picks up reflected signals. With this arrangement, the fast-moving missile can carry a far simpler equipment, and its reliability is enhanced manifold. As you can see, cooperation between the ground-based radar and its junior counterpart on the missile can take many forms.

## RADAR AT SEA



Seamen have not been slow in adopting radar either. Depending on her size, a present-day ship will carry from one or two to thirty-five radars (a battle-ship and an aircraft carrier is equipped with thirty to thirty-five radars, a cruiser with twenty, a destroyer with ten, a submarine with up to five units, and even a harbour tug now carries at least one radar). What does this big family of radars do?

To begin with, there is our old acquaintance, the search radar. It keeps watch on the overall situation and warns the ship's commander about the presence of other ships,

both friendly and enemy. The rotating aerial of this radar stands out clearly on any ship. It is set up as high as possible so that the beam can sweep clear of the superstructures and masts.

As with aircraft, the Navy likewise uses a radar system for the early detection of enemy ships to prevent them from approaching unnoticed. Very often, ships are equipped with radars to keep watch on the air. As dependable sentries, they protect the ships against an air raid. There are also radars which control the fire of the main batteries, anti-aircraft mounts, and torpedoes. In the home port, radar enables the ships to avoid collisions in any sort of weather. The latest types of marine radar ganged up with computers give a warning of the likely collision and enable the captain to steer an anti-collision course. To these should be added the radars on board the Navy's aircraft, the radars to guide the missiles fired by guided-missile ships, and the radars of the helicopters which seek and destroy submarines.

Now we shall take up in greater detail a radar navigation system which secures the safety of ships sailing off the coast, in river estuaries, and in harbours. One such system developed in West Germany covers the Baltic coast and rivers.

In 1958, the radar system was set up on the rivers Elba and Weser to ensure navigation at night and in fog. Later, it was extended to include a radar station in the port of Hamburg. The need for this system had arisen because shipborne units, although capable of detecting ships and measuring their ranges, could not give sufficient information about them. A ship-borne radar could not properly cover long stretches of a tortuous and fairly narrow river, and the radars set up on the river banks were to fill this gap.

In addition to the good knowledge of the area, the

operators of the shore radars use additional information from a variety of other sources. They keep the ships' captains informed about the situation on the route so that they can take whatever measures may be necessary in order to ensure the safety of traffic.

The navigable section of the river Weser stretching for about 60 kilometres from the Alte Weser lighthouse to Bremerhafen is very narrow. The situation is aggravated still more by the numerous sand bars flooded by high tide. To make navigation under the circumstances safe, four radars have been set up along the route. The maximum distance range of each radar is 12 kilometres, and its scope displays simultaneously all targets within a radius of six kilometres. Since the navigating channel of the river Weser is very narrow, the radars should be able to separate targets fifteen metres apart. The radar aerials are mounted on the towers above the lights, and so every means has been used by their designers to reduce the total weight of the aerials, scanner drives, and other equipment. In addition to the small size and weight, much has been done to make the radars reliable in operation and resistant to the effects of the maritime climate.

Radar information is processed at Bremerhafen where it is channeled over radio-relay links which are also used to relay control commands and messages the other way round.

At present, radar operators are using VHF radio sets to inform ships about the situation on the river and to warn them about likely hazards. In the prospect, radar data will be relayed to ships automatically. From these data, suitable instruments will reconstruct the situation on their scopes with the same crispness and definition as on the radar scopes. These instruments may either be carried along by a pilot or installed permanently on every ship.

A very narrow frequency band will be used for data transmission because the frequency spectrum is already crowded by the many stations operating in and around the river ports.

The originators of the system are contemplating provision of facilities for ship identification. Ordinarily, a radar target is very difficult to identify precisely even at maximum resolution and definition. As we have seen, in aviation this job is done by IFF units. Unfortunately, for the IFF system to operate, every ship to be interrogated should carry a responder. A way out is offered by another arrangement tried out in the ground-based shipping-safety radar system. For identification, the ship-borne VHF radio used for communication with radars is located by two VHF direction finders, and its location fixes the position of the vessel to be interrogated. In this way all vessels can be identified one by one.

For ease of watch on identified ships, a suitable code mark may be displayed on the scope next to the radar signal. In addition to the lines of direction to targets, the scope may also bear a map of the area or landmarks, such as buoys. When these are removed for the duration of ice drift in spring, their positions will remain marked on the scope.

Similar systems are in use in the Soviet Union. One has been in operation since 1955 at Odessa on the Black Sea, and other "radar leaders" are at work on the Baltic Sea and in the Kola Bay, doing their job on the trickiest parts of the fairway and near the ports where traffic is especially heavy. With a feeling of safety, the ship masters can sail at a greater speed, and this saves time and adds to the handling capacity of ports.

Another example of marine radar was shown at the Leipzig Fair in March, 1967. It is designed for in-

stallation on fire-fighting boats and will help fire fighters to see in a dense smoke when otherwise nothing can be seen a few metres away.

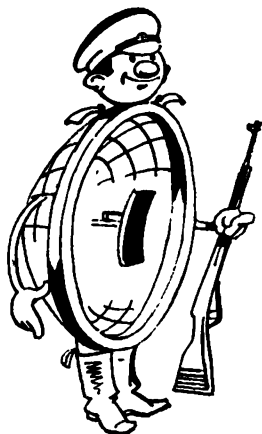
Radar also comes to seamen's rescue when they are forced to leave their ship and seek escape on life-boats. Known as "search and rescue radars", they are at the disposal of Coast Guard units. They can spot a life-boat carrying ship-wreck survivors at a distance of up to sixteen kilometres on very rough seas. After that, the lives of people are in sure hands.

## RADAR IN THE ARMY

Our story has led us to radar in the Army. While in the Air Force radar is carried by planes, and in the Navy on board ships, in the present-day Army (where the infantry in the usual sense of the word is no longer existent) radar travels on wheels or on soldiers' backs. This is why radars used in the Army are usual-

ly referred to as portable, pack-carried, transportable, mobile, and so on. For all their smallness, Army radars do important jobs, and no ground battle today could be fought without them. Of course, the top task of an Army radar is to keep watch on the battle field. As appears from the press, the following types of radar are now in service with the Army.

A portable field radar can detect a column of troops on march at a distance of 1.5 to 2 kilometres and a vehicle at



a distance of six kilometres. An up-to-date radar of this type weighs only 4.5 kilograms and has a remote-control facility so that the operator can be hundreds of metres from the equipment which is an attractive target for the enemy. It has no cathode-ray tube indicator and displays targets as notes varying in pitch and volume according to the type of target. A well-trained operator can easily tell a group of soldiers on march from a crawling scout, a track-laying or a wheeled vehicle. Some makes of this radar can detect even a nylon rope measuring a little more than three millimetres across and strung at a distance of 300 metres.

There are portable radars used as sentinels around vital installations. They can detect a man at a distance of 45 metres and a vehicle at a distance of 180 metres, and also determine their speed.

That is a good performance by any standards. Before it could be achieved, however, the designers had had to overcome a host of difficulties both because of the small size of the equipment and because of other factors. A major roadblock was ground return, as the echoes reflected from the earth's surface and fixed objects on it are called. When the beam of a radar points at the sky, it can only run into aircraft or missiles, and their echoes will stand out clearly on the scope free from any other unwanted reflections. When, on the other hand, the radar beam is directed at a grazing angle to the earth's surface, any structures, forests, hills and other objects will produce reflections of their own, and the wanted target will not at all be easy to discern among them. This is where CW Doppler radars (mentioned in a previous chapter) come in. They respond only to moving targets, and that is what is really wanted. Signals from fixed objects are cancelled, and nothing can interfere with the detection of moving targets.

Sometimes reconnaissance radars are mounted on helicopters. In one type, an ingenious method has been used to scan the earth's surface continuously. Usually, the aerial assembly is rotated by a separate motor. In this design, the aerial elements are built into the blade tips of the helicopter rotor—it has to spin anyway. Now it develops lift for the helicopter and doubles as a support for the rotating aerial.

In addition to reconnaissance, anti-gun radars contribute to the defence of friendly troops against enemy artillery or mortar fire and tactical missiles. They keep constant watch on the enemy's firing positions and as soon as they spot a flying gun shell, mortar bomb or missile they change over to tracking them. Tracking data are conveyed to a computer which plots the complete flight path of the shell or missile in a matter of seconds and determines the point where it has been fired from. The data are relayed to the friendly artillery, and this fires at once to suppress the enemy guns. The same radar that has detected an enemy gun, mortar or launcher controls the friendly fire by tracking the "friendly" shells or missiles and locating the points of impact.

As with the Air Force and the Navy, the Army uses air-surveillance, missile-guidance, and fighter-control radars. There are also some other radar types used solely by land forces.

Of course, the classification of radars we have used above is an arbitrary one. It has no room for, say, radar fuzes such as were fitted into artillery shells during World War II. A radar fuze is a veritable radar station; it has a transmitter, a receiver, and a power source in the form of a wet-cell battery which is activated by impact at the instant of fire. The fuze generates a burst order when the shell comes within the killing distance of the

target. Radar fuzes have greatly increased the effectiveness of artillery fire in air defence, in the Navy, and in the Army. So where does a radar fuze belong? Radar is doing well in all arms and services, protecting them against a surprise attack and enhancing the punch of present-day armed forces.

## RADAR AND SCIENCE

Now, how does radar stand vis-à-vis science? Has it forgotten all about its originators, scientists, in the tumult of activities? Fortunately, not. Relations between radar and science are those of mutual benefit. Scientists are continually improving radar technology, and radar pays back with all it can in the studies of nature.

For the first time, radiolocation techniques were used in ionospheric studies. As you remember, the precursor of radar was M. Bonch-Bruevich's ionospheric sounding station. The ionosphere looks like a puff-pastry in which each layer differs in electron and ion density. When this density in a particular layer reaches what is called the critical value, the layer will reflect radio waves. The critical value varies with frequency. By measuring the altitude at which radio signals of a particular frequency are reflected, one can readily plot the distribution of electron density across the depth of the ionosphere. Apart from a purely academic interest (to the physics of the Earth's atmosphere), these data are of high practical value—with a knowledge of the ionosphere's characteristics one can readily forecast radio-wave propagation at the various frequencies used in communications.

Radar has come to be an indispensable tool for weather men. Although we have already spoken about weather radar, the topic deserves a more detailed

discussion. The simplest method to watch the weather is to send aloft radio-sondes—balloon-borne instruments for the simultaneous measurement and transmission of meteorological data. A light-weight metal reflector attached to a radio-sonde will make it visible to radar, and this will be able to track it for hundreds of kilometres. In the process of tracking, the radar determines the speed and direction of the air currents that carry the radio-sonde. That is an indirect method of meteorological observations, however. Radar can watch clouds, storm fronts, and hurricanes directly. Present-day radars are good enough not only to trace the travel of cloud fronts but also to determine the rate of precipitation. In the United States, there are radars which can spot even the mysterious clear-air turbulences. The sensitivity of this type of radar is such that its operators boast they can tell a bee from a butterfly at a distance of sixteen kilometres. Weather radars are especially important in the watch of hurricanes and typhoons. On the basis of their findings, storm warnings are circulated to the ships sailing in the threatened areas and to the aircraft whose routes pass near the dangerous localities.

The efficiency of these systems is amazing. The central Aeroflot weather station which serves the airports around Moscow and uses up-to-date radar equipment served 200,000 flights in 1969 alone, and none of the airliners had to abandon its flight because of a faulty forecast.

With the present-day radar's ability to measure distances to an amazing degree of accuracy, maps of the earth's surface can now be compiled using radars, especially those carried by planes, so that great areas can be covered in a single run. Reports have been published, describing transhorizon radars capable of mapping the coast-line at a distance of several thous-

and kilometres. This is because sea clutter (as the echoes from the sea surface are called) comes in at a slightly different frequency than the echoes from the shore (remember the Doppler effect).

In the Arctic and Antarctic, large areas are covered by huge ice floes broken up by compression, heaping one upon another, compacted by winds, and cemented by frosts. Even the biggest ice-breakers fail against them. In such cases ice reconnaissance comes to help. Already in the early days of the Arctic Sea Route, planes helped seamen to ply the severe Arctic Ocean. A plane carrying ice observers would take off, and the observers would draw the ice fields and mark routes for the ship. Then the plane would pass over the ship at her masts' height and drop a message bag holding the map. However, even the best pilots could not sometimes fly a reconnaissance mission in the Arctic because of weather. That was visual reconnaissance. With the advent of radar, it gave way to instrument reconnaissance. For this purpose, an AN-24 plane carries a radar set bearing the apt name of "ICE-PACK". Every four minutes the radar beam paints an area of hundreds of square kilometres, a photographic camera takes shots of the radar display, and a detailed ice map is ready for use by ship navigators.

On one of these shots you can see a tiny arrow-head thrusting into a huge spotty heap of flaky ice. The arrow-head is the ice-breaker "KIEV" stuck in the north-eastern Kara Sea. The ice had solidly blocked the way for ships—neither the leader ship nor the convoy could make any headway. Now look at another picture: a fine whitish track is seen running around the ice mass and looping through the darker patches of clear water. That is how the "KIEV" led her convoy in a dense fog, following the route prompted by radar.

Here is another example. In the summer of 1969, a veritable downpour soaked the Ural area within the Polar circle for weeks, barring any chances for aerial maps to be photographed before prospecting parties were to set out on their treks. And again radar came to rescue. An AN-24 carrying the "ICE-PACK" radar took off from the Vorkuta airfield, looked through the rain clouds, and the austere face of the Urals with all of its wrinkles left its impression on film. The geologists could hardly believe their eyes—even aerophotographers had rarely produced photographs as crisp and clear in the fair weather.

The AN-24 has flown missions over the Bering Sea to help fishermen out of the ice, and in Turkmenia to spot underground sources of water. Invitations have come from railway builders to reconnoitre routes for their projects.

As we can see, radar has got a fairly good record of earthly services. Now it feels the Earth is too small for its capabilities. Time has come when it can step into outer space.

## RADAR IN SPACE

In 1946, radar men in Hungary and the United States picked up radar echoes from the Moon for the first time. Since then the Earth's natural companion has been sounded by radar more than once. Apart from accurately measuring the distance from the Earth to the Moon, radar has helped to test a number of hypotheses about the Moon's structure and surface. It is not hard to see how valuable this information has been for soft landing on the Moon's surface by Soviet automatic spacecraft and by the US manned Appolo spaceships.

In 1961, scientists in the Soviet Union, the United

States, and the United Kingdom picked up radar echoes from the planet Venus. The Soviet press carried detailed reports about the experiment for which the team headed by Academician V. Kotelnikov won a Lenin Prize.

The next steps in the development of space radar were radar soundings of Mars and Jupiter in 1963. The idea about the formidable experiments can be gleaned from these figures. The planet Jupiter is 1,200,000,000 kilometres distant from our home planet; it takes the signal one hour and six minutes to complete a round trip; the weak signal has to be accumulated for over twenty hours before it can be of any use. Now you can size up the efforts that had been put into the radar equipment so that it could sense a target separated from us by a huge distance. Yet Soviet scientists were able to solve all problems.

Later, radar men and astronomers in the United States bounced radar echoes off the Sun. In this case, too, the weak signal had to be accumulated for 17 minutes. For radar where time is kept by the millionths of a second, that is a long time, indeed. The experiment has yielded data about the radio emissions from the Sun, the motion of matter in the Sun's corona, and the speed of the solar wind.

Any one who keeps track of happenings in space exploration must know the important role that radar plays there. Putting spacecraft in orbit, tracking of satellites, soft-landing of manned spaceships, and searching for the returning spacecraft on land or water account for only a modest part of the tasks performed by radar. Rendezvous in space, docking operations, and the round trips to the Moon by the Appolo spaceships have demonstrated the high level of performance achieved by radar.

In 1970, Luna-16, a Soviet space probe, brought

back samples of lunar rock to the Earth. The accuracy with which the probe was orbited, its flight controlled, the drilling operations carried out, and the Luna-16 retrieved came as amazing fits to all who watched the experiment. Even specialists, usually very reserved in their opinions, did not stint their praises in newspapers and magazines.

A good proportion of the credit is due to radar. With it, the flight controllers steered the probe along its assigned path. Radar data furnished a basis for in-flight corrections. A radio altimeter brought in the probe to a soft landing on the Moon's surface. Radars saw the Luna-16 off on its Moon-bound journey, picked it up on its Earth-bound leg, and guided it to landing on the Earth. So, the success of this momentous experiment was a veritable triumph for radar.

Everyone is getting more and more accustomed to life in the space age. Leading newspapers carry items about the launching of a Cosmos satellite bearing a three-digit ordinal number on the third or fourth page now. The headlines of reports on the flight of a recent manned spaceship read simply "To Work in Space". Placed next to the common word "work", the word "space" is losing its romantic appeal. That is true—in near space man is getting down to brass tacks, and unmanned space probes go scouting to the other planets of the solar system. Welding sparks have marked orbits around the Earth, and Lunokhods rove busily on the Moon's surface. These remarkable vehicles which combine features conventional to us, Earthlings, and parts as if thought up by science-fiction writers, test lunar rock for mechanical properties and chemical analysis, and take stock of the Moon's relief.

Now what does radar do in space? We have already mentioned that not a single launching can do without radar. However, this does not exhaust the role

of radar. In the not so distant future, orbital spacecraft will carry radars not only for scientific experiments but also for more routine applications. In brief, these potential applications may be as follows:

(1) In farming and forestry: studies into the density of vegetation; distribution of forests, meadows, and fields; identification of soils, soil temperature and moisture content; watch on irrigation schemes; fire detection.

(2) In geography: trends in the use of land, distribution and state of transport and communication systems, exploitation of natural resources, topography and geomorphology.

(3) In geology: studies of rocks, stratigraphy of sediments, search for mineral deposits, development of novel techniques for prospecting and exploration.

(4) In hydrology: studies into the evaporation of moisture, distribution and infiltration of precipitation, investigations into the run-off of underground waters and contamination of water surfaces, distribution of snow and ice cover, watch on the state of the major rivers.

(5) In oceanography: studies into the relief of rough seas and oceans, mapping of the coast-line, watch on biological phenomena, ice reconnaissance.

Today, it is too early to define specific space radar systems that will be applied to these studies. Yet, it is not difficult to envisage the mammoth work they are to carry out.

From the above listing you can estimate, at least approximately, how many people are concerned with radar in one way or another. They make up a huge army of specialists who know what radar is like, how it operates, and what it can do. A far greater number of people however run into radar daily without realizing that radar is always among them.

## IT IS ALWAYS AMONG US

I bet I know what you are going to say. You may be a person far from the military or science. Yet it does not mean that radar is far from you as you might think. It is next to you always and everywhere. Do you not believe me? Then, have a bit of patience, stretch your imagination a little, and I'll be able to convince you.

Every year the time comes when people fall to think of their vacations. Some reckon solely on their resources and go vacating with no advance arrangements. Others (at least in the Soviet Union) expect assistance from their trade unions in getting accommodation. Victor, a friend of mine I'm going to talk about, undoubtedly belongs to the second category. So, well before his vacations, he did all he could to secure a good accommodation. What do people in the Soviet Union regard a good holiday accommodation? A few years ago that would certainly be a stay at a rest home or sanatorium on the Black Sea. Now vogue and the Health Resort Administration are diverting the streams of vacationers from the hot and overcrowded south to the cool, magnificent, and fabulously beautiful north. Today, the fashionable routes for vacations include cruises on the northern seas, or trips to Spitzbergen. So, it is an easy matter to guess why Victor was happy to have secured an accommodation at an international rest home in a picturesque locality bearing the poetic name of Thule in Greenland. Victor came back well rested, sun-tanned, and brimming full with impressions. For a whole week he kept us from work by telling us the same things again and again. What follows is a nearly word-for-word record of his story.



### *How I Went to Greenland*

"Well, I never! I had not been sure about my accommodation at Thule until the last moment. There was no time for packing up. I threw a pair of socks, two or three shirts, an evening suit, an electric razor, and a pair of pajamas in a suitcase, slammed shut the door of my flat, and jumped into the street. Fortunately, a taxi-cab drove up at the next house, an elderly gentleman with a mahogany walking stick and dark eyeglasses left it and went into the house, and the green "VACANT" light illuminated on the taxi to my relief.

"The airport, please, and as fast as you can", I said to the leather-clad cabby and took a fresh breath. The ticket was in my pocket, my suitcase stood next to me on the well-used taxi seat—everything seemed all right.

"Out of sympathy or, perhaps, in anticipation of a good tip, the cabby stepped on the gas and drove the taxi with little concern for traffic rules. As always happens in such situations, the traffic police were on the alert. Before long the blue-yellow Volga of a roving traffic patrol overtook and forced us to the curb. That meant a fine, which troubled me little if at all—to be at the airport in time for take-off was more important. We whizzed through a dark underpass, into a wide suburban highway, and past two or three settlements, made several tight turns, and came to a stop at the airport building. I did make it, after all! I climbed the passenger stairway several steps at a time

and plunged into the embrace of a soft chair. The airliner took off and broke through the low hanging clouds above the airfield into the expanse of the blue skies, filling the cabin with sun light and the travellers' souls with peace and blissful quiet. Before long the plane landed softly and stopped on the apron in front of the airport building. Another taxi-cab took me through an old seaport town with its magnificent buildings to the harbour. Laying alongside a pier was our motor-ship looking like an iceberg from the distance and like a disturbed ant-hill at close quarters. I had scarcely unpacked my things and settled in my cabin when the liner cast off, and the deck came alive under my feet. It would be unforgiveable to miss the ship's departure from the port — I went out to the deck, waved my farewell to nobody (just not to differ from the crowd at the hand-rails), and watched the liner manoeuvre between the ships on the roadstead and into the open sea. Picking up speed, the ship soon answered with a slow and measured pitch and roll to the waves. The haste was over, and everybody could now take a rest, the more so that the public-address system boomed all over the decks with the traditional cue of unsuccessful actors, "Dinner is served!"

"Having given its due to the meal prepared by the ship's cook, I went to the deck again for a walk. But the walk proved a failure — a dense fog hang heavily above the sea, masking everything and making me feel dank and cold. That was no tropics. Well, nothing doing. The best I could do was to go to sleep, consoling myself with the old adage that nobody had died of sleep yet. The next day we should be at our destination, and the quiet purring of the ship's big engines could work better than any soporific.

"The next morning we woke up to the beauty (yes, it was beauty all the same) of Greenland's coast. A short time later we were at the rest home. The weather was excellent, the meals good, and the company pleasant. Every evening we were treated to the local standing dish — polar lights. Everyone, except card players (the Russians played preference, and the foreigners mostly bridge and poker), went out, as if in a sort of ritual, to watch polar lights. The sight was stunning, indeed, no matter whether you saw it for the first or second time, and it would surely remain such for ever. Even the nearby huge buildings of whimsical architecture could not spoil it — they could well do as a background to the scenery. We were told they were a research establishment of some sort. They did not count anyway, and as to polar lights, they were magnificent. I'll try and describe my impressions. . .

Then a stream of vague interjections followed, expressing Victor's rapture, admiration, and similar feelings. They hardly need be quoted, the more so that nobody has yet been lucky enough to describe polar lights as they ought to. Polar lights hugged Victor with their shaggy paws and triumphantly waved their iridescent and irresistibly beautiful wings. Let them wave, and we shall go back to radar. I hope I have not led you away from it too far, have I?

So, back to radar. But where does it come in in this chapter? Not a word seems to have been said about it. Not a word? This only seems so. As a matter of fact, radar was in everything. As a proof, let's trace Victor's route once more, and I shall point to radar each time it turns up.

As I said, Victor took a taxi-cab left by "an elderly gentlemen with a mahogany walking stick and dark eyeglasses". Now keep the count on your fingers. The elderly gentlemen was practically blind, and the walking stick in his hand held a radar set used as a blind man's leader. The set measures distances to obstacles and helps the blind to take their bearings. That is a noble function, is that not? With a weight of about two kilograms, the leader works reliably. A similar radar leader can be built into spectacles. Mr. Spivak of New Zealand has been the first blind man to wear such spectacles. The three miniature radar sets built into the rims give out sounds to warn the wearer about the obstacles in his way.

Now about the fine that the cabby had to pay for overspeeding. This is for a second finger in your count. The point is that the traffic-patrol Volga carried a Doppler radar to measure the speed of the cars on the road. It is time for all overspeeders to tremble — before long all traffic-control patrols will be equipped with similar radars. The roads leading to Moscow have

come by the signs reading "ATTENTION! TRAFFIC IS UNDER CONTROL OF HELICOPTERS AND RADAR". Traffic officers have now got up-to-date facilities to keep order on roads and to prevent accidents.

The helicopters used for traffic control around Moscow are the KA-26s painted bright yellow and bearing the inscription "GAI" (for "state traffic inspection" in Russian). Sitting next to the pilot is a duty officer from a helicopter traffic-control squad. He operates photo and cine cameras and sound-reinforcement units slung under the wings. There is a separate radio set for communication with the Volga traffic-patrol cars moving in the same direction as the helicopter. The cars, too, carry radars to measure the speed of traffic to a high degree of accuracy. Should a car exceed the speed, the radar will show this on its scope and actuate a buzzer and a signal lamp.

Helicopters patrol the roads from a height of several tens of metres. Should an accident occur on the road, the helicopter will summon the nearest ground patrol at once or, if necessary, land near the crash to give first aid or take the survivors to a nearby hospital.

Apart from keeping order on roads, radar can help with steering cars in poor weather. The Philips Research Centre has recently demonstrated a microwave radar for cars. No matter how poor the weather may be, be it rain, fog or snow, the driver will see on his radar scope a clear picture of the road with all the moving and stationary objects on it to a distance of sixty metres.

As a safeguard against fatigue, negligence or lack of skills, it will be a good idea to fit your car with another novelty in radar engineering — a radar which controls the car brakes. In the United States, they sell one such gadget which can operate under two sets of conditions. One is for highway driving and the other for

city driving. On a highway, the radar will slow down the car, should it move within less than fifty metres of an obstacle. Whatever the speed of the car, the radar will bring it to a stand-still within at least two or three metres of an obstacle. When driving in a city, the radar will keep the car at a speed limit of 40 kilometres an hour, apply the brakes within nine to twelve metres of an obstacle, and stop the car within two or three metres. In expert opinion, motorists will queue up to buy the gadget.

Next comes the thing for your third finger — the underpass or, rather, a radar system that controls traffic there. In case you do not believe me, I can quote an example from reality. In mid-1966, an underwater tunnel over 1.3 kilometres long was opened for motor traffic near Amsterdam. An endless file of cars drive in several lanes both ways in the tunnel. Some twenty thousand vehicles pass the tunnel each way every twenty-four hours. With a traffic like this, even a surface road would require a traffic controller. This is more true of a road in a tunnel, and the job is done by radar.

Lined up along each shoulder of the tunnel roadway are thirty radar sensors. When a car moving in the first lane drives past a sensor, the sensor picks up an echo from that car and relays it to a central control room. The sensor cannot pick up echoes from the cars driving in the second, third, and succeeding lanes because they are screened by those in the first lane nearest to the sensor. It might appear that the system cannot control traffic if it "sees" only the cars in the first lane. This is not so, however. The point is that the system not only registers every car passing by, but also determines its speed. In fact, the speed is determined by a computer which accepts signals from the sensors.

When everything on the road is all right, the cars drive at a more or less even pace, say, at 60 kilomet-

res an hour, and no intervention from the computer is needed. Now imagine that somewhere down the tunnel the speed has dropped to nearly zero. That points to a jam, and urgent measures must be taken to clear it. This is done by the computer which switches the traffic lights and summons a wrecker, if necessary. It may so happen, however, that, instead of a slowing down, the cars in the first lane where an accident has occurred move into the second, and there will be no slowdown for the computer to respond to. In such a situation, the computer acts in a different way. Every car entering the tunnel is registered by all the sensors in turn, and the computer forms in its memory a sort of travel path for each car. Should a car move from the first into the second lane, its travel path in the computer memory will be broken, and that will point to an accident. The computer will sound an alarm and display the location of the accident on a TV monitor. The road radar also counts the cars that pass the tunnel and sees to it that every driver pays the tunnel toll, an important job, too.

In the meantime Victor reached the airport, a veritable kingdom of radar. Count the radars there yourself:

- (1) a weather radar;
- (2) an airport surveillance radar;
- (3) an air traffic-control radar;
- (4) a precision approach radar.

Now, let's see what Victor's airliner carried.

- (1) a search radar;
- (2) an instrument-landing system (ILS) which usually includes a radar altimeter, a Doppler radar to measure aircraft speed relative to the runway, and a few more;

(3) an anti-collision radar. It measures the positions and speeds of air-borne objects constituting a threat

to the parent aircraft, while an aircraft-borne computer plots their flight paths and steers the parent plane clear of other planes.

We have already taken up all of these radars. A few words are in order about one more radar utilizing the Doppler effect. It measures the vertical component of the plane's speed just before touch-down, and a fairly simple computer also carried by the plane calculates the force with which the plane strikes the ground. The instrument accumulates the data from touch-down to touch-down and determines when the long-suffering landing gear begins to yield to fatigue. That marks the end of service for the landing gear — it must be replaced, or else it will fail any moment.

So much for air-borne radars. Those set up on the shore included:

- (1) a weather radar;
- (2) a harbour traffic-control radar;
- (3) an off-coast sailing radar.

The motor-ship was equipped with:

- (1) a search radar (to steer the ship safely in fog and at night);
- (2) a mooring radar, an anti-collision radar, and one or two more radar types whose choice is determined by the vessel's speciality.

That is quite a number, although not so many as on a combat vessel.

At last Victor arrived at the rest home. Has the rest home got a radar, too? Doesn't that look like a radar sort of mania, you may ask? Yet, there is a radar station at (or, rather, near) the rest home. Remember "the nearby huge buildings of whimsical architecture"? They house a radar equipment to detect and track space probes, satellites and other space objects. Now that's all. How many have you counted?

In case you think the author has laid it on too thick,

I can prove my point by reference to newspapers. Let it be *Izvestia* of, say December 19, 1969. The fourth page carries an interview given by the Soviet Minister of Civil Aviation, which reads in part: "...Soviet scientists, designers and engineers have got down to a practical solution of the complex problem of automatic approach and landing under adverse weather conditions. This holds out the promise of putting an end to overdue planes and recalled flights". That is radar. On the same page we find a short news item. I'll quote it in full:

"The tanker "BRATISLAVA" of the Novorossiysk Steamship Line was sailing the Atlantic when the ship's radar showed an image of an unidentifiable obstacle. The officer of the watch reported the approach of a dark ball. The puzzled ship master alerted the crew, slowed down the vessel and had all portholes closed. In a few minutes the vessel ran into a huge cloud of black beetles. The beetles covered the deck and superstructures with a heavy and moving blanket, and found their way into every nook and crack. It took the crew a whole day to clean the vessel of the uninvited visitors. The alarm had been sounded in time".

As you have read, with all portholes closed, it took the crew a whole day to clean the vessel. If it had not been radar, the invasion would have been much more difficult to repulse.

If you take a Soviet newspaper on the eve of, say, Soviet Army and Navy Day, Missile Troops Day, Radio Day, Aviation Day, Frontier Guard Day or any other Day, you will surely run into quite a number of reports on the uses of radar. That will be enough, I think, to convince any reader, however distrustful, that he lives in a world saturated with radar. So it will make sense to take a closer look at radar.

# Part Two

## How It Works



## WHICH ONE TO CHOOSE?

Now we have got a general outline of radar. We have discussed a whole range of radars each of which does its job as best as it can. Unfortunately, our knowledge is lop-sided a bit. We know what each radar can do, but still do not know how. Now we shall fill the gap.

Which radar to choose? We might take up all the radars described in Part One. But, as one philosopher remarked, you cannot embrace the unembraceable. Or, as technical publications state, "the limited space available does not permit a detailed treatment of this intriguing problem".

So, we shall not seek an unattainable goal. Ours will be a simpler road. We shall see how a particular type of radar works. This will give us an insight into operating principles of all radar systems and into those of the radar of our choice. But which one to choose?

We might use several approaches.

One is based on the theory of probability. We might write the names of all radars on slips of paper, roll the slips, drop them in a hat, and ask an unbiassed person (who may be any schoolboy) to draw one. That would settle our choice of the radar to be described. A major advantage of the method lies in its complete

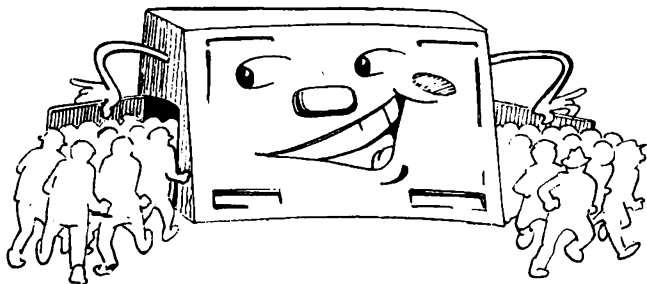
objectivity. Unfortunately, we might wind up with an obsolete or a highly specialized radar. As to highly specialized radar, the author would hardly be able to compete with technical books. Still more important, the reader would stand to lose much, as would the author himself.

Another relies on public opinion. A questionnaire listing the radar types that the author can describe intelligibly might be sent to every prospective reader who is supposed to cast his (or her) vote in favour of a particular type. The radar receiving a majority vote would be our choice. Although fairly good in itself, this approach entails a back-breaking amount of work to prepare and circulate the questionnaires, collect and process the answers on a computer (no self-respecting public-opinion expert would do his job without a computer nowadays). Anyone would simply hate to waste so much time on all these operations.

A third approach is one of a choice based on the author's sheer will. The reader can do nothing to affect it. The author makes his decision on the strength of his likes and dislikes and, especially, of the material he has about the various radars. Naturally, the author will respect the readers' interests too. Apparently, nothing can be done for those who may be unsatisfied with the author's choice.

So, we have made our choice. It is an up-to-date, high-power radar used to detect and track artificial satellites, unmanned space probes, manned spaceships, and ballistic missiles.

To begin with, a few words about what our radar station looks like. Picture to yourself a stand on a stadium. The building that houses our radar station is the same shape, although it is a little smaller in size. Where the stand has seats for spectators, our station has a receiving and a transmitting aerial. The building



proper is divided into rooms and halls for radar equipment.

Suppose we have passed exams in accident prevention and safety practices and been cleared for an excursion to the station. We fix the time for our excursion when the station is inoperative, because when it is running even its attending personnel will not be admitted to some of its rooms. As a rule, these are halls housing high-power units which sport skulls and crossed bones on caution signs to keep you from a closer acquaintance with them. Nor should we interfere with the work of the operators at the central console displaying meters and scopes. Their duties call for utmost concentration and watchfulness, so we'd better not to distract them.

Now we set out on our excursion. We walk from hall to hall, and can see about the same things everywhere: long arrays of iron cabinets (racks or bays, as they are called by radar men). Some of the cabinets are open; while the station is inoperative, engineers and technicians are doing preventive maintenance and replacing dubious components. If you peer into a rack, you will see an entanglement of coloured wires, heavy cables in plastic sheaths or metal braiding, a multitu-

de of valves, transistors and other parts embodying the latest advances in electronics, optics, mechanics and many more divisions of present-day science and technology.

We come into the central control room. Nobody can be seen around now. The blank scopes look dull and indifferent, the pointers on the many meters stand dead, and there is a dust-cover on the intercom microphone. When the station goes into operation, operators will sit down at their scopes, and these will come to life with a bluish or a greenish glow, swept across by electron beams blooming to a bright spot whenever the radio beam from an aerial runs into a target. All happenings will be recorded by cine cameras and magnetic tape recorders. At a later time, when everything is quiet, the operators will be able to analyse the records and say whether the station has operated properly. In the course of work, its operation is evaluated and target signals are processed by a high-speed computer-set up in the halls where we go from the central control room. To-day, no tracking radar can do with-





out a computer, and very often the efficiency of a radar is to a great extent determined by the capacity of the computer's memory and the speed with which the computer does its job.

We walk on and set ajar the door to a large hall packed with imposing devices. An electrician would immediately recognize transformers, rectifiers, and other devices supplying electric power for our radar. And they are imposing, indeed, for the radar when it is operating draws as much electricity as a medium-sized town would. Although they are idling now, their subdued low-pitched humming and everything around command respect, and we close the door carefully.

As any one may have noticed, sight-seers always quicken their pace towards the end of a tour. And so do we, passing with quick steps (not running — that would be improper) through the hall housing the systems that cool the electronic gear in operation, and other ancillary equipment.

That brings us to the end of our tour. What about your impressions? Did you like the radar the author

has chosen? If you did, go on reading to get an idea about how it works. Before you do that, however, we shall try and answer one more question.

## HOW TO TAKE STOCK OF AN ACQUAINTANCE?

It must be said from the outset that the author thinks the reader is a thoughtful young man weighing every step he is going to take. We take him *a priori* to be no idealist likely to fall in love over head and ears, but a person who can explain to people why he loves his chosen one. I wonder how a young man like that chooses a girl friend. I can picture it as follows.

On meeting a girl for the first time, he will try and take stock of her in terms of a small set of qualities or, as engineers say, variables. These may be the colour of her hair and eyes, the way she carries herself, the way she treats her friends, what sort of mother she has got, how she reciprocates his feelings, the time it will take him to see her home, and how many trains he will have to change going to his place after a meeting. . . That will be about all\*.

Some variables, such as disposition or height, are vital (as many young men will feel humiliated seen next to a tall girl); others (say, the size of footwear) may be of minor importance. Some variables can be measured upon the first meeting, others cannot (say the temper of the girl and of her mother). To follow the advice given in Ya. Khurgin's *So What?*, the best way will be to list all prospective acquaintances in a table, give each a mark for every quality, total the marks, and select one with the highest score.

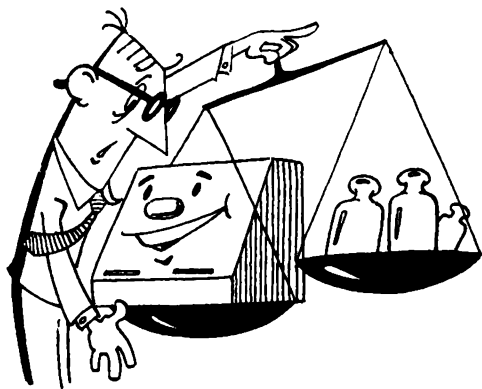
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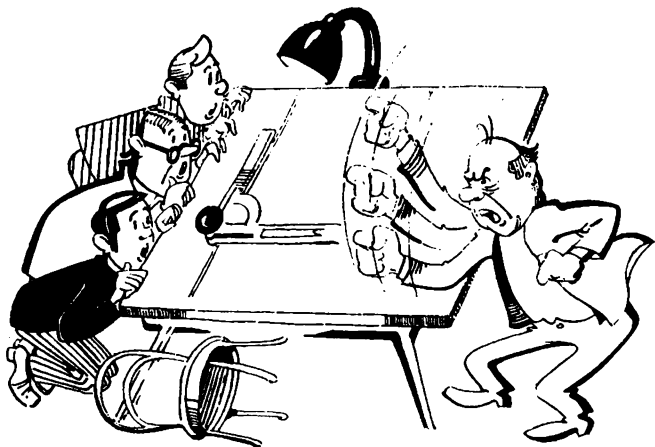
\* With the reader, different things may count, for

no two people are alike.

One way or another, we may take it that our young man knows (or thinks he knows) how to get about choosing a girl. We are a darn sight worse off. For one thing, we haven't the slightest idea how to grade radars. Should we count the buildings a radar station occupies or weigh its components? Even to a layman it will be obvious that with a yardstick like that we may find ourselves in a wrong position. Of course, today a

Mary	165
Betty	170
Peggy	





stronger and more sophisticated radar is bigger, but with further advances in miniaturization and micro-miniaturization the next generations of radar, although still more sophisticated in design, will be smaller.

To get an idea about how radars are graded, we shall introduce a new character, the customer. From the view-point of general progress, he is a positive factor, because by urging radar designers he drives them to turn out ever better systems. For the same reason, however, it may sometimes prove unpleasant to have any business with him — constant urging has never been among a person's merits, has it?

Our customer specifies a radar having a long detection range, high accuracy, high resolution, and high scan speed. That's quite a list for a single radar. Here we have run into four unknown terms at once. They call for an explanation.

Long detection range is another way of saying that he needs a radar capable of detecting sufficiently



small targets at as long a distance as practicable. The greater the distance, however, the more the signal is attenuated on its way to the target, and the weaker the echo. The situation may be likened to what is shown in the picture. Starting out on a Marathon race is a group of runners full of strength. Of them, only a few exhausted athletes (in our case, the echo signals) will reach the finish (in our case, a radar receiver).

For every radar there is a distance beyond which no echoes from a target can be detected or, less so, measured. The longest distance at which this can still be done is called the detection range. The detection range can be extended by packing more energy into the transmitted signal.

The radar that we have chosen for discussion sends out signals as separate pulses. With such radars,



the detection range is determined by the energy carried by a single pulse. In turn, the energy of a pulse depends on pulse duration and average transmitted power. Without going into further detail, it may be said that transmitted power cannot be increased indefinitely — that much is clear from simple physical considerations. If a radar is already operating at the limit of its power output, but the desired detection range is not reached, the energy carried by a signal can be built up by making each pulse longer.

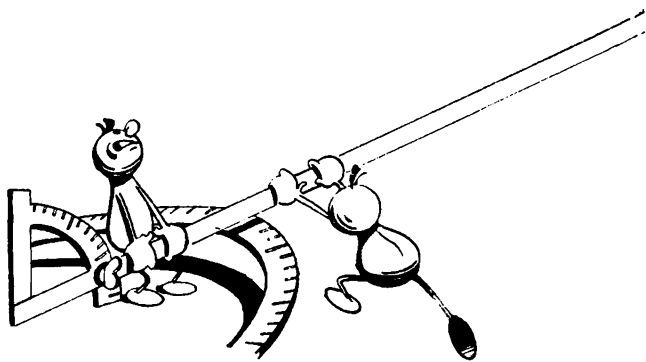
It would seem then that by using the maximum available power and the maximum pulse duration we could secure a detection range however long. But... In engineering, there is always room for a "but". This time the "but" comes from the second and third requirements specified by the customer — high accuracy and high resolution. To understand why long detection range conflicts with high accuracy and high resolution, we shall discuss, in a very elementary manner, how a radar locates a target.

## HOW A TARGET IS LOCATED

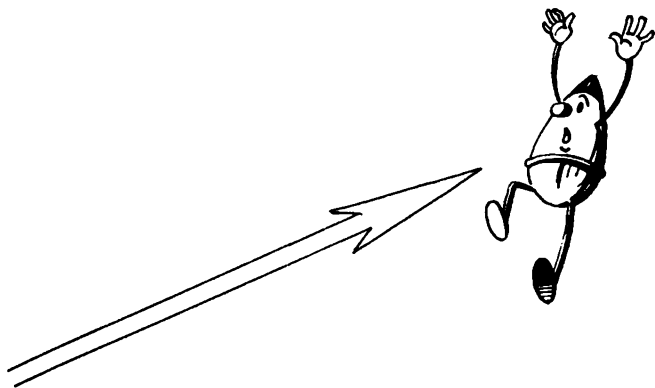
The position of a target is defined by its range, angle of elevation, and angle of bearing or azimuth. The azimuth of a target is the angle in a horizontal plane, measured from a reference (usually, North) in a clockwise direction. The elevation of a target is the angular position of the target perpendicular to the Earth's surface. The elevation and the azimuth (or, more correctly, the intersection of the planes containing them) produce a straight line on which the target is located, and the range pin-points where the target lies on this straight line. So, to locate a target by radar, one must measure its range and the two angles, azimuth (or bearing) and

elevation. Let us see how the range of a target is measured.

We turn on our radar, and its transmitting aerial sends out a burst of electromagnetic waves travelling at the speed of light towards the target. At the same time, the electron beam starts on its outward travel on the indicator screen from the point which marks the position of the radar set. The system that makes the beam sweep across the scope is arranged so that when there is no target the beam will trace out a luminous straight line on the screen. Let there be a target in the way of the outgoing radar signal. After the signal strikes the target, some of its energy will be reflected, and the echo will reach the huge dish of the receiving aerial. At that instant, a kink, or break, will be produced on the beam trace, identifying the target. The same happens to all succeeding signals. If the target is approaching the radar set, the signal will complete its round trip in a shorter time, and the break will appear on the trace at an earlier time. Since the speed at which the radar signal travels remains unchanged, the time in which the signal completes its trip to the target and back

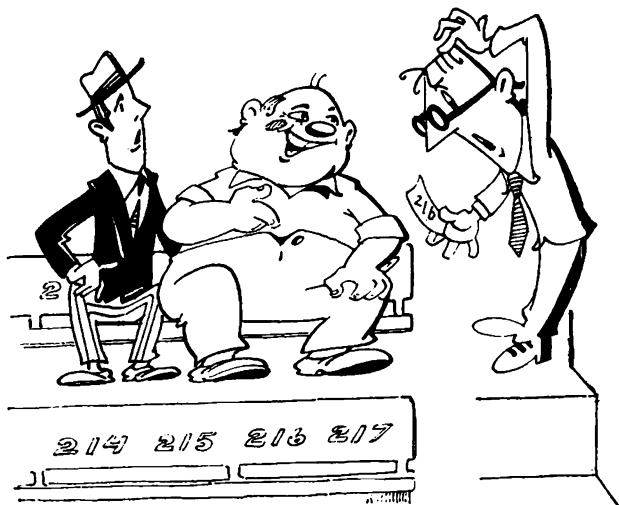


is proportional to twice the distance (or range) to the target. This round-trip distance can be measured, if we provide divisions on the indicator screen and make each division represent so many kilometres or miles. What we shall have then is known as the range scale. Now it will suffice to note the scale division at which a break is produced by the return signal, and the figure will give us the range to the target in kilometres or miles. The more there are divisions on the range scale, the



greater the accuracy with which the target range can be measured.

It would appear, then, that range accuracy might be enhanced indefinitely by making more divisions on the range scale. This is not so, however. Picture to yourself you are to watch a football game. You come to the stadium well before the kick-off and look for your seat, say No. 216. You readily spot seat No. 214, next to it a Gargantua-looking man, and past him, seat No. 218. Puzzled, you try to guess which seat the Gargantua should legitimately occupy.



About the same thing would happen if our radar set used a range scale with too many divisions — a target echo would span several divisions at a time, and the range operator would be at loss to tell the range accurately. One way out is to use shorter pulses. Then the target echo will be narrower and will not span two or more divisions at a time.

With shorter pulses, we can also satisfy the third requirement specified for a radar — high resolution in range. If two targets lie so close together that their echoes merge into one, radar men say the targets are not resolved. To make the thing clearer, look at the picture. Suppose you are looking at the players from above. On the left, you will see them standing apart, with the ball between them — that is, you have resolved these targets. On the right, you will hardly be able to

say how many players you can see, not to speak of the ball (remember, you're looking at them from above). The best you can see is a group of players, or, which is the same, you have not resolved the targets — to you they have merged into one. Now it is clear what resolution is.

As we make the outgoing signals shorter, the respective breaks on the scope also appear shorter. When the width of a break is made smaller than the separation between the targets, these will be resolved, and each one will stand out separately. Naturally, the customer would like his radar to determine both the range and the number of targets accurately. So, it would appear, shorter signals are the thing we need, aren't they? It has already been shown, however, that we need long signals. That drives us into a conflict again. There is a way to avoid it, though. For the time being, you may take my word for that, and an explanation will be given a bit later.

How does a radar determine the angles of elevation and bearing of a target? This job is done by a directional aerial. What does "directional" mean? As applied to an aerial, it means that the aerial radiates or picks up radio waves more effectively in some direction (or directions) than in others. Graphically this property is represented by what is called the directional (or



radiation) pattern, usually containing the so-called main beam, or lobe, and several side beams, or lobes. The side lobes show the small amount of power unavoidably radiated in (or received from) undesired directions.

Now suppose that the main beam of an aerial points precisely at a target. Then from the angle coordinates of the beam we can readily determine the angles of bearing and elevation of the target. Should the beam cover two or more targets at a time, the targets will appear as one, or will be unresolved in angles. To make these targets resolvable, we must use a narrower beam. When the beam is made so narrow that it will cover only one target in any position of the aerial, we may proudly tell the customer his radar secures complete angular resolution. Unfortunately this cannot be done for fundamental reasons. For one thing, the aerial beam cannot be made infinitesimally narrow (as will be shown shortly, this would call for an infinitely large aerial). For another, it may so happen that several targets lie all in the same direction. In a situation like that, we may be able to resolve them in range, but we shall fail to do so in angles.

In practice, however, one never insists on "infinitely good" performance. What is usually sought is simply good performance. As regards a radar, it should resolve targets lying fairly close together. "Fairly close together" may mean different things, depending on the function that a given radar is to carry out. Sometimes a resolution of a few minutes or even degrees will do; sometimes, the limit will be set in seconds of arc.

So, a narrow beam determines the angle coordinates of a target to a higher degree of accuracy because there will be fewer overlapping positions than with a broader beam. This amounts to using a scale with a greater number of divisions. That means that we should



give preference to a narrow beam. How can a narrow beam be obtained?

From radar theory it is known that the beam width is mainly determined by the size of the aerial. The bigger the aerial, the narrower the beam, the higher the accuracy with which the angle coordinates of a target can be measured, and the higher the resolution. Of course, the wavelength used by the aerial must remain unchanged. To sum up, the customer's radar needs a big aerial. Leaving out purely technical limitations, nothing seems to stand in the way of building a radar aerial of any size, however big. True, if we made an aerial several kilometres or tens of kilometres long, we would have to take into account the curvature of the Earth, the difference in temperature between the ends of the aerial, and many other things. Fortunately, there are other ways out, short of using very big aerials.

So far we have dealt with a target falling within the

aerial beam. There is nothing, however, to guarantee that the target will fall within the beam of its own accord. This is the reason why the radar aerial is usually made to look for targets actively.

Early radar sets were mounted in vans, with the aerial set up on the van top. In searching for targets, the van would be turned bodily together with the aerial and operator about a vertical axis, while the van chassis remained stationary. In this way, the aerial beam searched continually the surrounding space through  $360^\circ$ , and targets were detected in any direction. The faster the rate at which the van was rotated, the faster the beam searched every patch of the sky, and the more unlikely it was for any target to be passed unnoticed.

The rapidity with which the radar aerial is rotated is called the speed of scan and is expressed in scans per minute or second. So long as planes flew at low speeds, they could reliably be detected at low scan speeds. With faster planes, however, a slow-scan radar would miss them. So the need arose for higher scan speeds. Unfortunately, that could hardly be done with the vans, for the operators sitting inside them would feel like an astronaut whizzed about on a centrifuge, thinking more of their spinning heads than of work. This is why in the later makes of radar sets the operator's cabin and all equipment were made stationary, and only the aerial rotated.

With the advent of supersonic planes, satellites, and, especially, missiles, travelling at high speeds, radar came by aeries several tens of metres long. There is no way for rotating an aerial that long. Instead of mechanically scanned aeries, those with electronic scanning, often called phased arrays, have come into use.

For a better insight in the workings of phased arrays, we shall again use an analogy from sports.

This time I invite you to a swimming pool. Eight swimmers precisely equal in skills and strength are to reach the finish, climb out of the water, and gather together. Let us stand at the finish wall and watch the swimmers. Since they are equals, the swimmers will be moving all abreast, in a direction at right angles to the finish wall. They will reach the wall and climb out of the water all at the same time, so that we shall see the eight men at the same instant. Now let the swimming pool be irregular in shape, with the start wall at right angles and its finish wall at an oblique angle to the sides. In this (non-existent) swimming pool, the swimmers will appear swimming in a staggered fashion, in a direction at an angle other than the right one to the finish. The swimmer on the shortest lane will have climbed out of the water when the others will still be in the water. If the pool is such that the difference in time between the swimmers on adjacent lanes is one second, swimmer No. 1 will wait for the last one to touch the wall seven seconds, swimmer No. 2 will do that for six seconds, and so on. It is only when the last man climbs out that we shall see them all together.

Now to go back to our aeri-als. Let a big aerial be made up of an array of dipoles, or small self-contained aeri-als in their own right. If radar signals come from a direction at right angles to the array, they will reach the dipoles all at the same instant (as swimmers do in a pool regular in shape). These signals may be added together and routed to the succeeding stages of the receiver. If radar signals come from other directions, they will reach the dipoles at different times. Before they can be combined, the signals coming first should be delayed until the last dipole accepts its signal (as in a pool irregular in shape). This is done by electronic circuits known as delay lines, and each dipole has a delay line of its own. The more the direction from

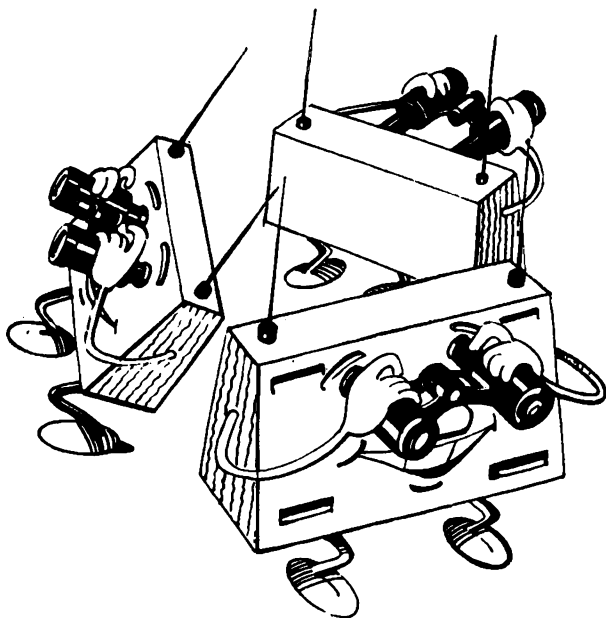


which signals come in differs from the perpendicular to the aerial, the greater the delay from dipole to dipole. By varying the delay, we can control the direction in which a phased array can "look". The signals arriving in this direction will be combined, while those from other directions will not, because for them the delays will differ from the difference in time between the arrival of signals at the various dipoles.

The reader may ask, why is it that the signals from the various dipoles of a phased array must be combined? For one thing, this is how aerial beams can be formed and scanned rapidly in azimuth and elevation. For another, a combined signal is stronger and more convenient to receive and process.

All that has been said fully applies to a phased array used as a transmitting aerial. Through delay control, we can send the composite signal in any direction of our choosing. A sophisticated electronic system varies the delay in each dipole in a predetermined manner, and the aerial beam searches space for targets. That is how a phased array works.

Although a single phased array can search only a limited region in space, this region is held under constant watch as a whole. For all-round (360-degree) coverage we shall need several phased arrays, each taking care of its apportioned sector. With this arrangement, the speed of scan will depend on that of each array. Does the customer want a high speed of



scan? Well, with enough money and effort, this can be done, too.

Now, let us sum up what we have learned. We know that about half the customer's requirements can be satisfied. What we still owe him is to settle the conflict between the remaining requirements. As often as not, a way out of any situation is through a compromise. This will be discussed in the next chapter.

### HOW RADAR DOES IT—I

Not to tax the reader's patience, a straightforward answer may be given although it may be a bit difficult to grasp at once. The conflict is settled by using an ap-

propriate signal and by processing it upon reception in a matched filter. Now a more detailed explanation follows.

Well before radio engineers translate drawings into electronic hardware and builders erect steel and concrete structures, specialists in R & D (research and development) departments begin to rake their brains and to break their lances (that is, fountainpens) in arguments as to what signal the would-be radar set is to use. For the problem is formidable, indeed.

To begin with, let us recapitulate what sort of signal this should be. For one thing, the signal should pack enough energy. With a limited instantaneous power output, this implies that the signal should be as long as practicable. However, for high accuracy in target location and resolution, the signal should be as short as possible. For another, the customer would like to have a signal that can be discriminated and detected against the background of strong noise and interference. What aggravates the situation still more is the great multitude of noise forms. These include atmospheric, receiver noise, man-made noise or interference from nearby electrical plant, and what not. In the time of war, one will have to reckon with the enemy's jamming, or deliberate interference. It is in this discordant chorus that the faint and feeble target echo should be discernible.

Of course, there are many more requirements in the customer's specification, but those listed above will do. It is clear that the R & D men face a tough problem.

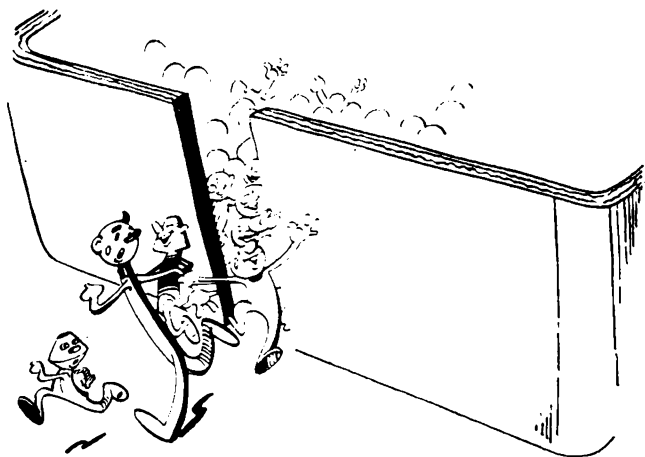
To make things still more difficult, the engineers who will turn out the final hardware insist that the R & D men should keep closer to earth. Above all, their ideas, however brilliant, must be realizable at the present-day state of the art, and at reasonable cost for that matter. The best choice to them would be a radar

set that can be built from existing components well tried out in practice. That would save time and effort, and the set would be completed earlier and operate more reliably. Sometimes, however, old circuit configurations and components will prove inadequate, fundamentally novel hardware will have to be developed, and this will again entail a conflict of interests between R & D men and production people. This is where a compromise comes in—the former trade in something for a concession from the latter.

Of late, R & D men seem to have been getting the upper hand. It is not hard to understand why. At first, radar progressed mainly through improvements in equipment performance—ever more powerful transmitters and bigger aeri-als were built, and yet untapped wavelengths were tried out and accepted. Finally the point was reached where no more improvements could be squeezed out of existing designs, while the requirements were growing still more stringent. That was how R & D men took the lead. They had shown that further improvements in radar could only be secured through the use of suitable signals and of novel methods for their detection. That was a big qualitative jump in the science and art of radar. It took place at about the same time in the Soviet Union, the United States, the United Kingdom, and Germany during World War II.

The signals that have saved radar from stagnation, much as the famous geese saved Rome from destruction, go under a variety of names. They are called complex, broad-band, noise-like, pseudo-random, composite, and by some other names. So much for terminology; let's get to the essence of the matter.

Wise men, of whom there are many among radar theoreticians, have spotted a loop-hole in the conflicting requirements for the radar signal. On the one

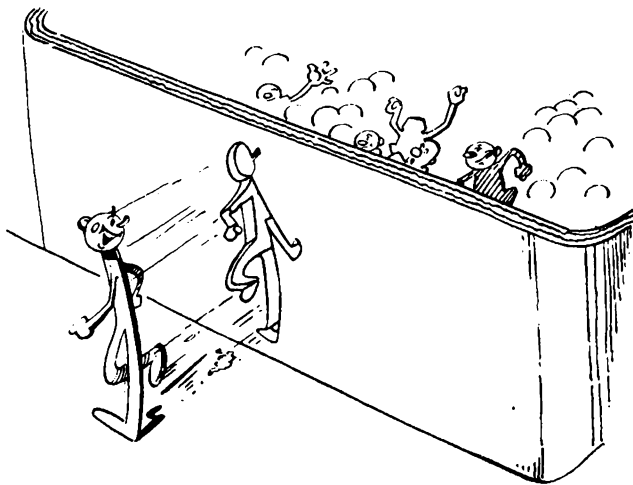


hand, we need a long signal for transmission (so that the signal can pack more energy), on the other, we need a short signal for reception (for better resolution and coordinate determination). Isn't it possible to generate signals which would be longer in transmission and shorter in reception? As it turns out, this is quite feasible. When the requirements were couched in appropriate terms, a whole range of signals that can be compressed in a radar receiver were suggested.

In presenting the developments in this way, we sin against history a bit. Actually the things happened as follows.

Some thirty to thirty-five years ago when the early radar sets just made their appearance, nobody cared for high accuracy in ranging or resolution. What was needed was a simple and workable equipment capable of detecting targets in whatever manner it could. But already at that time radar specialists were concerned—

among other things—with the input circuits of radar receivers, usually called filters. Like ordinary chemical filters, they should separate the incoming mixture of signals into the individual constituents. In our case, a filter is to extract the wanted signal from a mixture of signal, noise, and interference. In radio engineering in general, and in radar in particular, it can be done by tuning the receiver to the frequency band where the signal is expected to occur. You do this job when you tune your receiver in search for dance music or a football reporting. In radar, the frequency of the expected signal is known in advance because we send out the signal ourselves. So, the filter in the receiver should be tuned precisely to this frequency. Then all other unwanted signals and noise will not stand in our way, except the interference having frequencies falling within our frequency band. As a rule, such signals are difficult to filter out.



Specialists make it a point to optimize whatever they lay their hands on. In this case, too, they were eager to turn out an optimum filter, that is one passing best the wanted signal and blocking or suppressing effectively interference and noise. Mathematicians did their bit—they solved the optimization problem and decreed that, except minor details, an optimum filter should have a frequency response neatly tailored to the frequency characteristics of the signal.

In other words, for each signal there should be an optimum filter which would fit only that particular signal. Such a filter should be not only tuned to the signal frequency, but also take into account the manner in which the signal frequency may behave within the selected band. Should the signal carry more energy at some particular frequency, the filter would pass that frequency better than the frequency at which the signal carries less energy. Such a filter is said to be matched to the signal. Hence the name—a matched filter. It is difficult for signals of any other waveform, even occupying the same frequency band, to pass through a matched filter. If they do break through, what is left of them will hardly be discerned against the background of noise passed by the filter. This happens so because the filter has not been matched to them. While an ordinary frequency filter may be likened to a wicket through which any passer-by can walk, a matched filter acts like a hole in a fence which would pass only a person whose figure is properly “matched” to the hole outline.

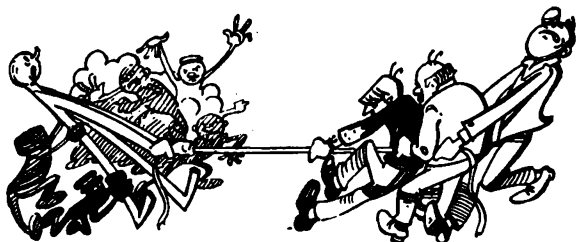
So, the goal had been achieved, a filter that could separate effectively the signal waveform from perturbing noise had been developed. It had been christened “matched” and taken to engineers to be translated into hardware. It turned out, however, that this could not be done—the engineers had not yet come by the val-

ves, delay lines and other components essential to pseudo-random-signal generators and matched filters. The "brainstorm" ideas of R & D men were left lying in the files of patent offices as elegant but useless things demonstrating the prowess of human thought.

With further advances in technology, however, the requisite components were finally developed, and radar specialists took a renewed interest in matched filters. By the early 50s, radar research laboratories in almost all advanced nations were busy investigating how matched filters could be put to work.

At first they were incorporated in "breadboard" models, then in prototype radars. In short, matched filters had become a practical reality. Almost at once one more interesting feature about them was discovered. Sometimes the output signal of a matched filter would have a waveform differing from that of the input signal. The signal amplitude would rise while its duration would be shortened. This happened when the signals had a sufficiently great base (the base of a signal is defined as the product of signal duration by frequency band). So, it had been found that the greater the signal base, the more it would be shortened and the greater its amplitude would rise above the noise level. If we were interested in preserving the waveform of the received signal, we should treat this as a nuisance and should make whatever we could to get rid of it. Since, however, we are interested in detecting a signal, that is, in establishing its very presence, the rise of the signal peak above noise is to be welcomed.

You have probably noticed that the words "noise" and "interference" come in frequently. Of course, the reader knows what they mean in everyday life. Their precise meaning to radar, however, needs an explanation. Let's have a closer look at them.



## NOISE—WHERE IT COMES FROM AND WHY

So, we are going to talk about noise. Chances are every reader has a definition of noise of his (her) own. To some, it may mean the screeching and gnashing sound of a tramcar passing by under their windows at night, others may identify it with the buzz of voices in a reading-hall, still others may think of something else. What is common to all of these forms of noise is a sort of sound that acts upon our ears. A radar set picks up and processes signals with no sound heard at all, however. What is, then, noise that makes itself felt in radar?

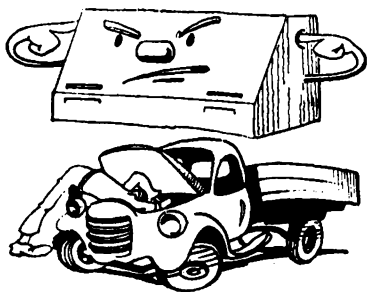
All began, it appears, with radio operators who had to catch Morse signals from among the whistling, howling, crackling, hissing and clicking sounds heard in their earphones. To them, that was noise in the usual sense of the word. Radar which has developed on the basis of radio engineering has borrowed and retained the name. It has come to denote any perturbation interfering with signal reception. To an operator sitting at a radar scope, noise appears as random spikes on the beam trace, merging into a fringe. When small in amplitude, the fringe is called, a bit affectionately, grass (look at the drawing on page 88. It does look like grass, doesn't it?). If the noise pattern

is strong and the echo signal is feeble, we are in for some unpleasant developments. For one thing, we may miss the wanted signal among noise. That means a missed target with all the accompanying consequences.

What these consequences may be the reader can picture to himself with a very little stretch of his imagination.

For another, a strong noise pulse may be taken for the wanted signal and reported through the proper channels. That might mean a false alarm, an unpleasant event, too. True, a skilled operator can sometimes pick signals with an amplitude well below that of noise. The point is that noise pulses occur at random, now appearing and now vanishing, while the wanted signal is more or less stationary and turns up at one and the same place on the beam trace (provided the target is not a moving one). That is enough for a skilled operator to tell it from noise. In a sense, the operator then acts as a fairly good filter. Unfortunately, the reliability of this detection is low.

Where does grass come from and what is it that forces the beam trace to move up and down rather than to sweep quietly across the base line? The point is that the atmosphere around the Earth is filled with electromagnetic waves. The radio waves produced by thunderstorms or polar lights, or by electric plant ranging from large power generators to the ignition systems of cars (this case is shown in the accompanying drawing), large broadcasting transmitters, and amateur VHF radio sets account for only some of the



sources of natural and man-made noise and interference. When added together, these perturbing signals give rise to a noise voltage in the aerial, varying at random with time. At one instant, the noise voltage may be low, and the beam trace will not practically depart from the base line; at another instant, the noise voltage may rise, and the trace will stray away. This appears as grass on the radar scope.

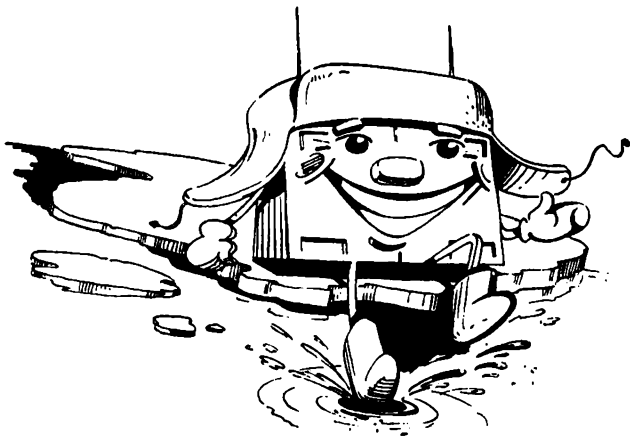
Another form of noise is thermal, or Johnson, noise generated by circuit components\*. It is especially troublesome in the input stages of a receiver, because the wanted signal is weak, and thermal noise may be comparable in magnitude with it. In the succeeding stages both the wanted signal and thermal noise will be amplified by an equal amount. Therefore, the closer a source of thermal noise to the receiver input and the greater the number of amplifying stages that thermal noise passes, the more harmful it will be. A variety of means is used to minimize thermal noise, even by cooling the early stages of the receiver. A reduced temperature brings down thermal noise, but cannot eliminate it, altogether. This is why thermal noise always contributes to the grass seen on a radar scope.

To make a picture of noise complete, a few words are in order about cosmic noise. This is due to sources outside the Earth's atmosphere. Being very weak, it does not practically affect operation of conventional radio receivers. The sensitive radar aerials, however, pick them up all the same, and cosmic noise may sometimes mask the wanted signal.

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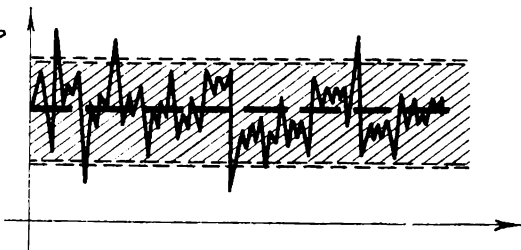
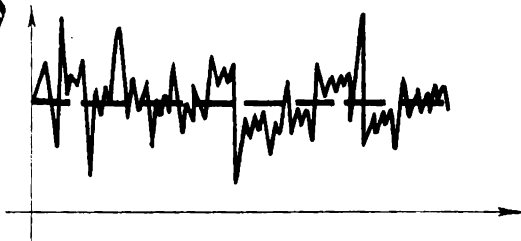
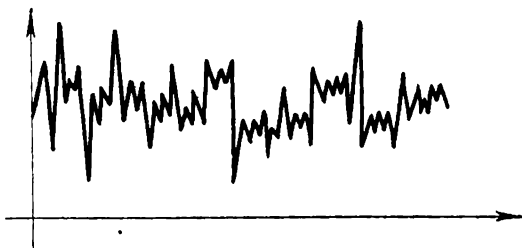
\* Electrons in metals are relatively free to move at random. The higher the temperature of a circuit component, the stronger this random motion. Since an

electric current is the motion of electrons, their random motion generates the random signal known as thermal noise.



Noise varies in strength continually. Therefore, in order to describe noise, we have to use quantities obtained by some sort of averaging the individual noise pulses. Most often, use is made of the mean noise value (that is, a value obtained by averaging the individual noise pulses over a long stretch of time) and its variance (defined as the deviation of the individual noise amplitudes about the mean). With these two quantities we can readily predict the probability of occurrence of very strong and very weak noise pulses.

Let us take a record of some noise process and draw a line representing the mean, and two more lines, one above and the other below mean, with the separation between each of these two lines and the mean being equal to three times the square root of the variance (that is, three times the standard deviation). We shall then find out that the amplitudes of practically all noise pulses fall within the area bounded by the two outer lines. On the average, as few as three noise



pulses have any chance of extending beyond these boundaries. In other words, if the wanted signal is so strong that it exceeds the upper boundary of the noise band, we shall be able to tell the wanted signal from noise pulses in practically all cases. If, on the other hand, the wanted signal is so weak that a great number of noise pulses are comparable with or even exceed it in strength, we shall hardly be able to detect the signal.

Apart from noise, the wanted signal has one more enemy, interference. What sets interference apart from noise? An analogy will show the difference. Suppose you are sitting in a theatre. The curtain has not yet been raised, and a steady hum can be heard in the auditorium. It comes from the spectators talking in low voice, the steps of those hurrying to take their seats, the creaking sound of the seats, and so on. It does not stand in the way of your conversation with your neighbour. Now the curtain goes up, and silence falls in the hall. You are all engrossed in the action of the play when somebody near you goes to comment the hairdo or dress of the leading character. Only one person is speaking, and in an undertone, for that matter, but you can no longer follow the actors on the stage. So, the hum in the auditorium is like random noise in a receiver, and the neighbour's talking is interference. Another example of interference is an importunate acquaintance breaking into your conversation with somebody else only to tell you a stale joke.

To sum up, in technical language an interference is defined as a sufficiently strong and non-random signal causing an undesirable response of a receiver. It may come from one source, such as a nearby radar station or, which is much worse, from several sources.

Sometimes it is necessary to class noise and interference according to energy distribution. If the electrical

energy of noise is evenly distributed throughout a broad frequency spectrum, that is, if its energy is the same within any portion of that spectrum, we speak of white noise. If, on the other hand, the energy of noise is greater in some portions of the frequency spectrum than in others, we have coloured noise. The names are taken from the analogous definitions of light. If a luminous radiation contains all frequencies of the visible spectrum to the same extent, we shall see white light. If one frequency or group of frequencies predominates, we shall see a coloured light beam.

Radio engineers like white noise and strongly dislike coloured noise. The point is that they know better how to design a receiver and control the effects of noise when it is white than when it is coloured.

Thermal noise may be taken to be white, while the composite noise from stray sources of radio emissions may be coloured. This happens when there are more noise sources or the noise is stronger in some particular part of the frequency spectrum.

Interference, too, may be classed according to energy distribution and duration. You may run into narrow-band continuous interference. At audio frequencies, an example is the monotonous howl of a siren. At radio frequencies, this may be the continuous sinusoidal wave radiated by an extraneous generator. If this wave is sufficiently strong and falls within the frequency band of a radar set, it will produce a luminous bar spanning the entire width of the radar scope, so that the operator may fail to detect targets.

As often as not, radar men run into still another form of noise, called impulse noise. As its name implies, perturbing signals come in as pulses of short duration. A short pulse occupies a broad portion of the frequency spectrum, this region increasing as the pulse is made shorter. Because of this, impulse noise may interfere



with operation of radar sets using widely differing frequencies. Arrival of a noise impulse at a radar aerial may produce a spike on the beam trace, which the operator may well take for a target echo. As noise impulses grow in number and strength, the operator finds it increasingly more difficult to identify the wanted signal.

Although it may sound strange, an operating radar set may sometimes produce its own interference already mentioned as ground return. The term ground return (also known as ground clutter) applies to confusing, unwanted echoes from fixed objects, such as large buildings, hills, factory stacks, and the like, which interfere with the observation of desired signals on a radar display. Of course, the ground clutter may be avoided by lifting the aerial so that the ground and the fixed objects on it are outside the field of vision. Unfortunately, that would leave a very large sector not covered by radar. Another way out has been used in the United States. They have built a metal fence

32 metres high and 670 metres in diameter around a radar set. The metal net with meshes measuring a half-inch square, attached to a steel framework reliably keeps returns from the surrounding mountains and large buildings from reaching the aerials.

There are still other forms of interference, all meddling with normal operation of radar sets in one way or another. In some cases, interference may be unintentional—a “radio ham” may have trespassed on a frequency band allocated to another station or a careless driver may have parked his car with a faulty ignition system near a radar set. Those are all unpredictable source of interference. What we may be sure of is that in the case of war the enemy will make it a point to create deliberate interference to radars. This type of interference, or jamming, will be taken up later on.

At the dawn of radio, the operators were solely concerned with reception of the desired signal, with or without noise. They would be happy if there was no noise, and would make a wry face otherwise—noise had to be put up with as an inevitable evil. That was an era of non-resistance to noise and interference. Later, they came to think of how to get rid of noise. As an answer to the problem, the selective frequency filter was developed, followed by the matched optimum filter. With it, a good proportion of noise differing in frequency from desired signals was eliminated. But even this filter would pass much noise. That was how the idea of signal accumulation was brought out. In brief, signal accumulation is as follows. Suppose two signals come in one after the other, of which the first is delayed until the second comes, and then the two are added together. Since the two signals are fully identical, their sum will be twice as strong as each. On the other hand, noise pulses originate at different

times and may be out of step with each other. It may so happen that the noise pulse arriving with the first desired signal is positive while the noise accompanying the second signal is negative. When added together, they may cancel out completely or leave a negligible difference signal. As a result, the total noise pulse will distort the total signal less. As more and more signals are added together the noise will be attenuated greater, and the total signal level will rise higher above the total noise level. Unfortunately, this method cannot be used just everywhere. So we shall take up, for the time being at least, a single signal. That brings us back to the core of our discussion and we, equipped with knowledge of noise, shall see how radar does it.

## HOW RADAR DOES IT—II

As we have just seen, the higher the amplitude of the signal, the easier it is to tell it from random noise pulses and to establish the very presence of a target echo and, as a consequence, a target with greater reliability. In other words, it will pay to build up the signal in amplitude, even at the cost of some distortion. As has been noted, this can be done by using long-base signals and matched filters.

To begin with, we shall select an appropriate signal. Radar sets like the one we have chosen as an example have traditionally used pulsed signals, that is, portions of sinusoidal waves. With these signals, the bandwidth is fairly rigorously related to pulse duration, and their product is a constant, usually not exceeding 2. An increase in the duration of a pulse signal will immediately bring about a decrease in its bandwidth, and the other way round. This is a sort of situation aptly described by an old adage, "While you pull out your

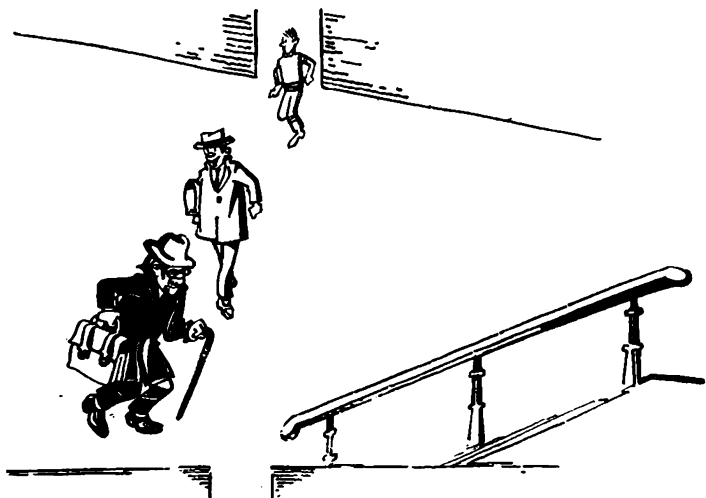
tail, you have your nose clinched". Since the signal base remains unchanged and small in value, this sort of signal will not suit us. Why? As already noted, the longer the signal base, the more it can be shortened, that is, compressed in a receiver. This compression builds up the desired signal in amplitude and improves the accuracy with which the instant of signal arrival can be determined.

Let us try another approach. We shall use a long signal and have it sweep in frequency during transmission. The swept-frequency signal will occupy the entire frequency spectrum or, which is the same, will have a broader bandwidth. Now, instead of a segment of a sinusoidal wave, usually called an elementary signal, we have got a more complex signal. With this complication we can break the vicious circle of small-base signals and obtain a long-base signal. The more the signal frequency is swept in transmission, the broader the signal bandwidth. With a sufficiently long pulse duration, we can get a signal base of 100, 1000, or even greater. Radar theoreticians have called these signals "complex" because their internal structure is not so simple as that of elementary signals. To production men, they are complex too, but for other reasons. The signal-shaping circuits and matched filters that go with these signals are complex, indeed. Small wonder, therefore, that in present-day radar sets a matched filter is by far the most important and expensive piece of equipment. Its performance determines that of the entire radar set.

Now we have generated a long signal with a sufficiently great base and sent it out to a target. On being reflected from the target, the signal reaches the receiving aerial and is routed to a matched filter. Let us see how the signal is compressed there.

The idea of signal compression is simple. Yet, for

better understanding, an analogy will be a help. Picture to yourself a long stairway in a college, and three persons heading for it. The first to reach the stairs is an old and grave professor. A little short of breath and mindful of his heart, he will not run up, but will climb the stairs slowly, with a measured pace. A couple of minutes later, an assistant professor, full of strength and in the last fit of youth, follows carrying an attache-case, a sort of insignia of his solid position on the college staff. He might well run up, but aware of his reputation, he thinks better than that and climbs the stairs unhurriedly, but faster than the professor. In two or three minutes more, a student turns up and climbs the stairs several steps at a time. If the stairway is long enough, the assistant professor will finally catch up with the professor and the student will overtake both. Since the author has complete con-



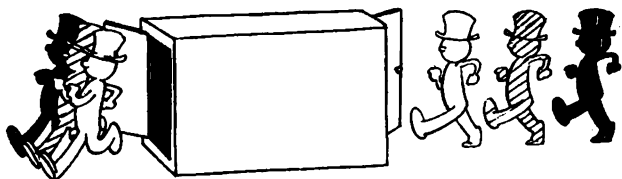


trol of his characters and of everything in his book, he chooses to cut off the rest of the stairway when the three men happen to stand on the same step. Now we can sum up the events we have conjured: at the bottom of the stairway, the student was 400 to 500 metres distant from the professor; on the final step they stand together. The length of the professor—assistant professor—student procession has obviously shortened because the three men walked at different speeds.

Now let us go back to a swept-frequency signal. We break it down mentally into three samples and, as a rough approximation, take it that each has a distinct frequency of its own. The next step is to find a device in which signals differing in frequency will be propagated at different velocities. In radio engineering such

devices are called dispersion delay lines. They are called delay lines because signals travel through them at a slower pace than they would do in conventional conductors or in a vacuum. To an external observer it appears that the signals are delayed for a predetermined length of time. They are called dispersion because a signal at one frequency is delayed more or less than a signal at another frequency. Exactly this property of a dispersion delay line will be utilized.

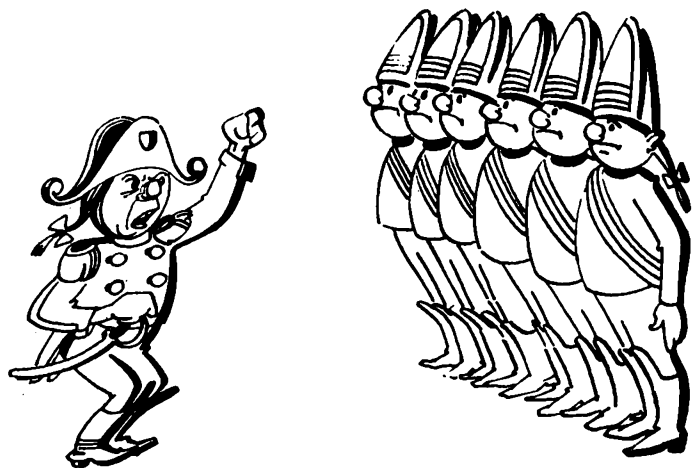
We choose the parameters of the dispersion delay line such that the signal samples differing in frequency and applied to the line input in turn will appear at its output all at the same time, and make the signal samples follow so that the one propagated in the delay line at the lowest velocity comes first, the one propagated in the delay line at the highest velocity comes last. Then the first sample will enter the delay line also first, but will travel along it more slowly. The second sample will enter delay line with a lag equal to the duration of the first sample but will travel faster. The lag of the third sample is the sum of the durations of the first and second samples, but its velocity is the highest. If we have designed the delay line correctly, the three samples will be superimposed on one another at the output, that is, will be added together, and the original signal will turn out shortened, or compressed, precisely to one-third of its original length. In our example, the signal base is of the order of three, and this is why the signal has been compressed to one-third of the original length. Generally, for any signals the amount of compression is determined by the signal base. With a base of 100, the output signal will be compressed to one-hundredth of its original length. With a base of 100,000, the output signal will be compressed to one-hundred thousandth of its original length. That is an impressive figure!



So, we have compressed the signal, but the signal energy, leaving out the losses in the delay line, has remained the same. As a consequence, its amplitude should rise markedly. Try and pour the water from a wide but shallow plate into a high but narrow glass. You will see that the water level in the glass will be much higher than it was in the plate. The same has happened to our signal after compression. The signal will stand out clearly above the noise level, and the reliability of its detection will be enhanced many times.

We have discussed a swept-frequency signal, also known to specialists as a frequency-modulated signal (like the signal itself, its name has also been compressed to "FM signal"). This is not the only type of signal that can be compressed in a matched filter. Besides, the FM signal suffers from a number of demerits that make it unsuitable for some special cases. We shall leave out these rather complicated situations and proceed to examining another type of signal. Instead of varying the frequency of signal during transmission, we can do this with its phase while leaving the carrier frequency unchanged. Of course, the signal phase should be varied in a predetermined manner rather than erratically.

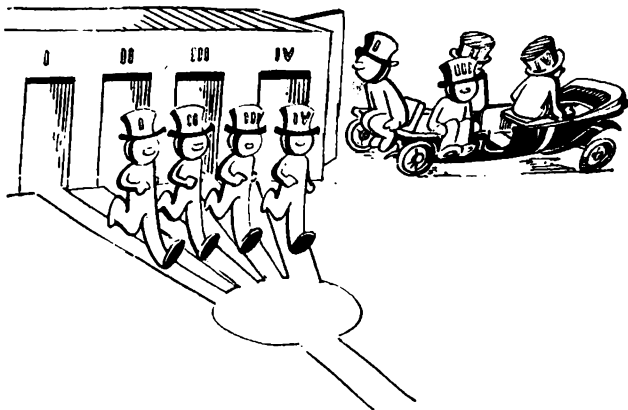
Look at the picture showing a rank of green recruits handled by a tough officer. In the upper drawing, the soldiers all face the officer—let us take it they are



"in phase" with the officer. If some force turned them about (through  $180^\circ$ ) with their backs to the officer, the recruits would be in what might be called "anti-phase" with him. To believe historians, the "anti-phase" attitude meant penalty of death to the courtiers of some kings. We shall not be that intransigent. Now the officer orders: "About Face!" To old rankers, that would be an easy matter, but not to the green recruits. As you can see, the rank looks rather disorderly (we shall omit the officer's remarks for obvious reasons, the more so that the disorderly rank suits our purpose).

Now, in place of each soldier, imagine a sample of a sinusoidal wave. If we take a single short pulse (one soldier), its spectrum will be fairly broad, but its base small. If all pulses are in phase (like the orderly rank of soldiers in the top drawing), we get a continuous sinusoidal wave of long duration, a narrow bandwidth, and again a small base. If, on the other hand, the pulses in the total signal are arranged at random (like the soldiers in the bottom drawing), so that they are all out of phase with one another, the signal spectrum will be broad, and the signal duration fairly long (equal to the sum of the durations of all the pulses). Because of this, the signal base increases considerably. For a signal composed of a hundred individual pulses, the base will be a hundred times that of each pulse.

Lack of symmetry in phase distribution among the pulses is essential to effective compression. In order to compress such a signal, we must delay the signal samples arriving first, adjust the phases of all the samples so that they will all be in phase, and add together the samples. The samples coming first can be delayed by a delay line, as in the previous case, the phase can be adjusted by phase-shifters, and the in-phase samples



can be added together by a summator. In contrast to FM signals, however, for which a delay line should have only one input and one output, a delay line for phase-modulated (PM) signals should have a multiplicity of outputs. Such a line is much easier to make and adjust because it is not a dispersion type and does not call for a perfect match between the delay line and the signal frequency, as is the case with the FM signal. From the fact that a delay line for PM signals is not a dispersion one and also that all the signal samples have the same frequency it follows that the various signal samples are propagated along the line at the same velocity.

A delay line for PM signals should be long enough to accommodate the whole of the signal, and have a separate output for each signal sample. The signal sample arriving first travels the whole length of the delay line; the sample taken mid-way along the signal has to travel only half of the delay line; the last signal sample is not delayed at all. With each signal sample

emerging from an output of its own, the samples will leave the delay line all at the same time and enter the summator. If the phase (say,  $0^\circ$ ) of a particular signal sample suits us, no phase-shifter need be provided at the respective output. If a signal sample is in anti-phase, a phase inverter will have to be included. With all of these arrangements, the signal samples will all be in phase and appear all at the same instant. The signal appearing at the output of the summator is compressed and its amplitude is boosted. The net result is the same as with FM signals.

Should any signal samples sneak through unauthorized outputs, the unsymmetrically arranged phase-shifters will shift their phases as the spirit moves them, and the summator will accept about an equal number of signal samples in anti-phase. Since the sum of two signal samples in anti-phase is practically zero, the sum signal will be negligible. This is why we have stressed the importance of the random arrangement of signal samples differing in phase. It is only when signal samples pass through the authorized outputs that we can derive a strong compressed signal. Any other signals will not be compressed, and the output signal will be small. A filter built around such a delay line is matched to the PM signal by locating phase-shifters precisely as the anti-phase samples are disposed in the signal.

We have already noted that it is a hard job to build matched filters for complex signals. This fully applies to both FM and PM signals, although the difficulties are different (but their extent is about the same). With FM signals, the main difficulty lies in securing a perfect match between the frequency response of a delay line and the signal frequency and in maintaining this match in the face of varying temperature or humidity, jarring, or chance changes in the character-

ristics of the circuit components. With PM signals, a delay line involves a multiplicity of accurately positioned outputs and the use of phase-shifters. One way or another, the problems that have to be solved are tough.

We have seen how a long signal is compressed in the matched filters of radar receivers. Signal compression kills at least two birds with one stone. For one thing, the signal stands out more clearly among noise. For another, it is much shorter, and this, as we have already learned, improves the resolution of radar sets.

Theoretically the extent to which the performance of a radar set can be improved is proportional to the signal base. Unfortunately, the longer the signal base, the more complex the signal structure. A PM signal with a base of 1000 should consist of 1000 discrete samples with their phases distributed in a predetermined manner. With such a signal we run into an extremely difficult problem of making a matched filter. At present, matched filters are most commonly based on tapped delay lines, with each tap terminated in a phase-shifter. For a signal made up of 1000 samples the delay line would have to have 1000 taps and about 500 phase-shifters (about half the signal samples will have a phase that need not be changed), and a rather sophisticated summator would have to be used in order to add together the 1000 signal samples.

But there is more than that to it. On travelling along a delay line, the signal is weakened, or attenuated, as specialists put it. This is because the materials of which the delay line is built absorb a sizeable proportion of energy. So the drawing on page 101 is a bit inaccurate. If we could draw a long delay line with a thousand outputs, the little men representing the signals would all be different in height. If the entire

signal is to be reproduced faithfully, it is important that all the samples (that is, the signals from the various outputs) have the same amplitude. To meet this requirement, we must provide amplifiers on many of the taps, especially at the end of the delay line. That means a further complication of the matched filter. To this we must add a host of other devices necessary to protect the filter against the effects of variations in temperature, jarring, and interference from adjacent receiver units. It is small wonder, therefore, that radar theoreticians were urged to find a simpler way for signal compression avoiding the use of difficult-to-build matched filters.

### A SIMPLER WAY

A simpler way to compress the signal is to use a correlation detector. This device has two inputs, one accepts the received signal, and the other, a so-called reference signal. The reference signal is actually part of the transmitted pulse which is allowed to leak off to the correlation detector over a delay line. In a sense, the correlation detector compares the two signals and, if they are identical, produces a narrow and strong peak at its output. This peak is precisely like the peak at the output of a matched filter. If the applied signals are different, the correlation detector will produce an insignificant signal hardly discernible against the background of noise.

In the above example we assumed that we knew in advance when the reference signal should be applied to the correlation detector. Actually, this is not so. Before we can know when the reference signal should be applied, we must learn the distance to the reflecting object, and this exactly is the final goal of any radar. As you see, we find ourselves in a vicious circle.

It can be broken by feeding the reference signal to the correlation detector intermittently. If no target echo reaches the aerial at any particular instant, the correlation detector will only accept the reference signal and the noise always picked up by the aerial, and no output signal will be produced. When, on the other hand, the correlation detector accepts both the reference signal and a target echo, a strong compressed signal will appear at its output. At that instant, the radar display will show a bright spot representing the target. A major drawback of an intermittent reference signal is that one is forced to use elaborate delay circuits and circulators. As often as not, these devices are comparable in complexity with matched filters, and this brings to naught the advantages offered by the simple correlation detector (which is actually a combination of a conventional multiplier and an integrator). Fortunately, radar sets operating on the correlation principle have about them a very valuable quality—the waveform of the signals they use can be varied at will. What is necessary for this purpose is only to modify the oscillator that generates the outgoing pulses. This modification will in no way impair the operation of the correlation detector because the reference signal is taken from the oscillator, and its waveform will change automatically just as the transmitted pulse undergoes a similar change. In a receiver using a matched filter this cannot be done because we cannot possibly re-adjust the complex structure of the signal-detection circuits.

Why is it that this quality is so valuable? Picture to yourself a radar set using a single form of signal in operation on the battle field. The enemy's electronic reconnaissance troops continually search for all radars using any frequencies. If they manage to pick up a sufficient number of signals from our radar, that will

be enough for the enemy to piece together a complete picture of its frequency, pulse duration, and even the waveform of the individual pulses. With this intelligence, the enemy can use powerful transmitters to generate signals which can hardly be told from those actually transmitted by our radar, with the result that our radar scope will display echoes from non-existent targets.

There are other ways for the enemy to jam our own radars. For example, he can generate strong noise signals spanning the whole of the frequency band used by our radars and making impossible the observation of any targets, true or false. This is where the correlation principle turns out to be a big help. With the transmitted signal continually varying in waveform, there is little for the enemy to do.

As compared with the matched filter, the correlation detector can use a wider range of signals. In addition to the already familiar FM and PM signals, a correlation receiver can use samples of random noise processes. No matched filter can be built for this sort of signal, and the signal itself is not at all easy for the enemy to detect—it can readily be mistaken for ordinary noise. But even if the enemy manages to detect the signal, its characteristics can hardly be measured.

In the final analysis we can see that the correlation detector and the matched filter have each merits and demerits of its own. The decision as to which is to be used should be taken in the light of a particular situation, the objectives sought, and ease of manufacture. Yet, be it a correlation detector or a matched filter, the physical basis of signal detection is the same; we simply compress the reflected signal in order to improve reliability of target detection and target resolution.

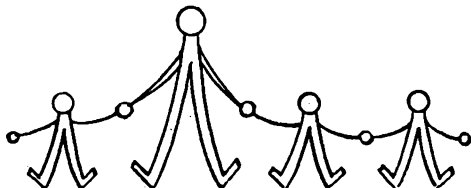
Much as any useful thing has an unpleasant side to it, so the compression of pulse signals entails some side-effects. These will be discussed below.

## UNINVITED COMPANIONS

It would appear we have done all we could. The signal has been raised well above the noise level and shortened so that any target can be pin-pointed with sufficient accuracy. Now it is time for the ideas to be translated into drawings and circuit diagrams from which builders can set up the metalwork, and assembly men can put together the equipment. The radar station will then be given a trial run and handed over to operators who will detect or track targets. Unfortunately, quite a number of snags have still remained uncleared, the worst offenders among them being what are called side lobes.

The point is that the compressed signal never leaves a matched filter or a correlation detector alone—it is always accompanied by its juniors, side lobes (also called signal residuals sometimes). Although they are small, the side lobes have to be taken into account because they are troublesome for at least two reasons.

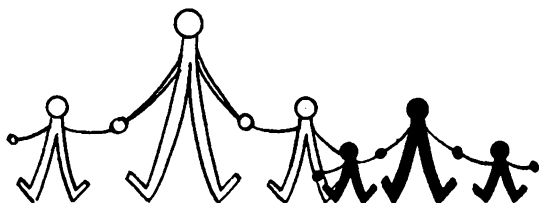
Firstly, side lobes add to the noise level near the compressed signal. Should any one of the side lobes line up with a noise pulse, their sum will be strong

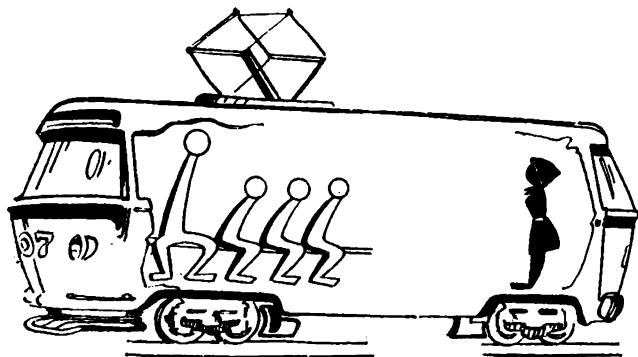


enough to produce a false echo, and this might lead to a false alarm.

Secondly, the side lobes distort the actual radar picture even though noise may be negligibly low. Suppose that the strength of the biggest side lobe is one-tenth of that of the main signal and also that the aerial picks up two echoes, each from a different target. It may so happen that one, say the second, is one-tenth as strong as the other. Then the biggest side lobe of the first signal will be comparable in strength with the second main signal. You will hardly be able to tell which is which in a situation like that. To make it still worse, the second true echo may be weaker than that, while the noise may be stronger. Then the picture on the radar display will be a complete mess, and you will run the risk of missing the second echo. If you know for certain that there must be a second target in the area and are eager to pick its echo, you might well take the side lobe of the first signal for the echo from the second target, the more so that a side lobe looks as steady as a main signal. That would be as bad as missing an echo, because you would have placed a target where there is none.

That is why side lobes are a nuisance. Yet, they cannot be done away with completely. The point is that side lobes change in proportion to the associated main signal. Should the desired signal rise in strength ten-



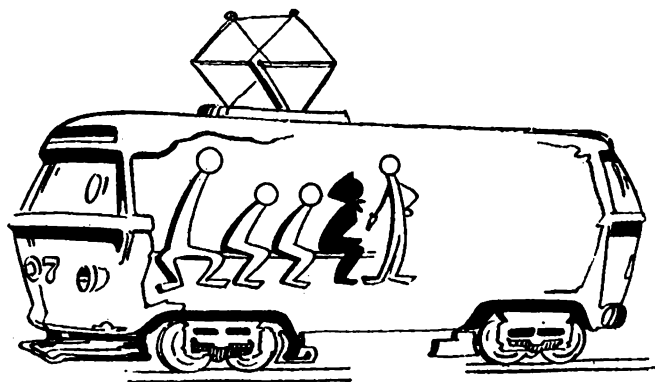


fold, the side lobes will do that in the same proportion; with a decrease in the strength of the main signal, they will decrease in the same ratio. Also, the side lobes tend to conserve their overall "volume". If we manage, in one way or another, to reduce some of the side lobes, the others will gain in strength by the same amount. True, there are ways and means of reducing the side lobes at least in part, but they are rather complicated and not always reliable. We have also to reckon with the fact that in reducing the side lobes we may distort or cut down the main useful compressed signal. So, radar specialists have to put up with side lobes, only seeing to it that they do not grow too strong.

The pattern in which the side lobes arrange themselves is different with different radar signals. Ordinarily, they span an interval twice the duration of the uncompressed signal, with the compressed signal occupying the middle of the interval. With some signals, the side lobes cover uniformly the whole of the interval and are about equal in strength. With others, the side lobes are all different in strength, the biggest ones appearing either near the compressed signal or at the edges

of the interval. Through a proper choice and adjustment of the signal, we can obtain practically any desired arrangement of side lobes. In fact, we may even be lucky to get rid of them completely in some small part of the interval. It is exactly this quality about the side lobes that radar men try to use to advantage.

Suppose we know when we may expect the appearance of an echo from the second, smaller target. Then we may use a signal which will have a small or no side lobe at that instant. Now we shall be able to detect any target, however small. The fact that the side lobes appearing at other instants will grow in strength is of minor concern to us. If we know that targets are traveling closely together, we can clear of side lobes the room near the compressed signal much as room has been cleared for the girl in the picture below. Or suppose we know in advance the area where a small target can be found (which is rarely the case in practice). Then we may remove side lobes from the respective part of the interval. If we know nothing (time or place) about the second target, we are free to choose a sig-



nal with which the side lobes are of medium strength and fill uniformly the whole of the interval. With no advance intelligence about the target, that will be the best choice.

To cut a long story short, for each specific case there ought to be a signal best suited to the situation on hand. Radar theoreticians have so far failed to devise a signal that would be equally good everywhere. Nor does it seem feasible. The author shares the pessimistic note struck by Woodward, a leading radar authority in the United States, in that the crucial question which signal is best for radar remains practically unanswered.

## HOW TO SEND OUT A SIGNAL, RECEIVE AN ECHO AND LOCATE TARGET

It is time to talk a little more about the radar transmitter. As always, we shall begin with an analogy.

Suppose you are to find something in a completely dark room. Depending on circumstances, several situations may arise. We shall take them up one by one.

*Case No. 0.* You are to find a small object, say a pencil. There is no light in the room, and no flashlight with you. Groping in the dark, you will find nothing, I bet.

*Case No. 1.* You are to find a clock with a luminous face or an old acquaintance of ours, the cat. There is no light in the room, nor will it be necessary. Just enter the room and look around attentively. The clock (or the cat) will tell you where you can "locate" it for sure.

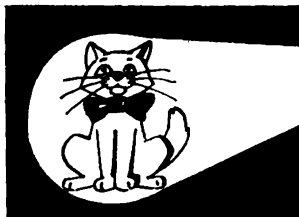
*Case No. 2.* As before, you are to find the cat. Now you have taken along a flash-light. You turn it on and play the light beam (like a burglar in a detective film) on the places where the cat is likely to hide. You will



surely find it, no matter where it hides—under the bed or in the wardrobe.

*Case No. 3.* That would be the simplest case of all. You can turn on the ceiling lamp and see any thing in the room. Perhaps you will have more than once to turn around or to bow or to stand on your tip-toes in order to peep in all the nooks (but this would be immaterial).

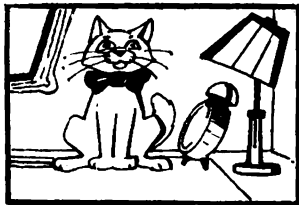
With this inventory of analogies, you will find no difficulty in learning how a



radar set searches for targets. You will only need to match them to similar radar situations.

*Case No. 0.* This is of no interest from a radar point of view. The set is simply turned off, and no target can be located.

*Case No. 1.* The target itself sends out signals matched to your receiver.



The radar transmitter is turned off. This is why non-radiating targets or targets radiating signals not matched to your receiver will not be detected. On the other hand, as we sweep the radar beam across the observation sector, we can spot radiating targets and determine their angular positions. True, we cannot determine the range, because we do not know the instant when the target signal sets out on its journey to our aerial. This is passive radar. A major advantage of this system is that it detects targets by their own signals without sending out any, that is, without revealing its presence. Its disadvantages are obvious. You can hardly hope that all targets will radiate signals, and those matched to your receiver, for that matter.

*Case No. 2.* The radar transmitter sends out exploring pulses in a predetermined manner in turn to every point within the observation sector. The receiving aerial is rotated or tuned (in the case of a phased array) so as to pick up reflected signals from within the narrow "illuminated" cone. In fact, one and the same aerial may be used for transmission and reception. To send out exploring pulses the aerial is connected to the transmitter. After the transmitter pulse has been radiated, the aerial is connected to the receiver, and the set waits for an echo to arrive during a time interval over which a signal can come from a target at the longest range. Upon reception of an echo, the aerial is moved on in angle, and the transmit-receive cycle is repeated all over again. This is active radar. Targets are detected irrespective of whether they wish so or not. The most crucial step in this case is to switch the aerial between transmitter and receiver. Sometimes, engineers may have to rack their brains a good deal in building a suitable aerial switch (or duplexer, as it is called).

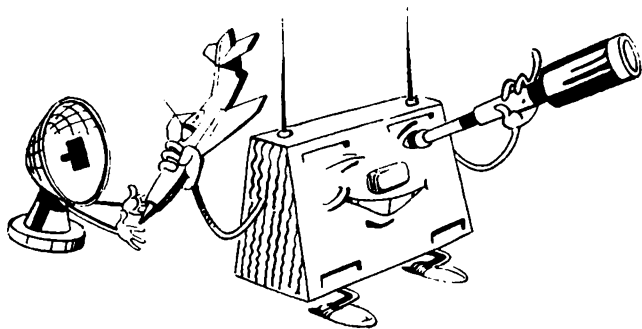
*Case No. 3.* A radar set may use two aerials, one

small and the other big. The small aerial transmits a broad beam which illuminates a large area or even the whole of the observation sector. The big receiving aerial with a narrow radiation pattern (essential to precise determination of angular positions) searches the observation sector for likely targets. The manner in which the receiving aerial searches, or scans, the sector may in no way be related to the type of scan used by the transmitting aerial. Now fully independent of the transmitter, the aerial may scan the sector line by line as if reading a book, or in a spiral, starting at the edges of the sector and working towards its centre. Should any part of the sector reveal something special, we may lock the beam on that part for whatever time may be needed.

The recent trend has been to put a computer in control of the radar beam. A computer alone can take stock of the situation in a particular area without undue delay, establish whether there is a target there or not, and instruct the servo drives to point the aerial at another area.

Once a target has been detected, we may either track it, or remember about it and search for another still undetected target, or do both. All depends on whether or not a given target is worth while tracking. The answer depends on the type of target. If it is a peaceful weather satellite, we may let it keep flying. If it is a missile, the computer or the operator will have got enough to rack its or his brains deciding.

Today it seldom occurs that radar sets operate alone. As a rule, they work as a coordinated group, with a clear-cut delineation of duties among them. Those with a longer range performance act as search radars. Once a search radar has spotted a target, it will hand it over to its junior (or juniors) with a shorter range of detection for tracking and switch back to



searching for other targets. With the target to be tracked properly designated or with its position accurately indicated, the tracking radars need not waste time for searching. They simply lock on the target and follow it in its travel. So that they can keep on the right track, they are given the flight path of the target. Mathematicians have devised ways and means for projecting a short segment of a target's flight path both ways. So, after a target has been observed for some time, we can, in principle, shape its flight path as a whole in a matter of seconds. If it is an artificial satellite, we can determine its orbit. If it is a ballistic missile, we can put our finger (more or less accurately) on the point where it has been fired and the point it is going to hit. Then appropriate authorities will decide what is to be done, but this is the subject for another book.

Before we conclude this chapter, it should be stressed once more that our story has left out quite a number of manners in which radar sets can operate. For example, in tracking a distant target we may use secondary radar. With secondary radar, the target carries both a receiver and a transmitter combined in

what is called a transponder. The receiver picks up a weak interrogating signal from a ground based challenger and triggers the transmitter (called the responder) to send a reply instead of a weak reflected echo in the direction of the interrogating radar. Unfortunately, not just every target will choose to carry a transponder— obviously, enemy targets will not.

Besides, to the multitude of existing radar modes of operation every self-respecting radar designer is eager to add something of his own invention as best suiting the problem at hand. So, we simply cannot cover all types of operation. With this closing remark we give up and go on to the next chapter.

## EVERYTHING IS SORTED OUT

Now we have at least an idea of what the signal should be like so that a radar set can serve its purpose. The customer may rest content—we have gone out of our way to meet his requirements. The turn has come for production men.

It should be admitted from the outset that a newly-born radar will fall short of its designers' expectations. It is only after de-bugging the various components and the equipment as a whole that the set will approach the goal or even work better than that. For progress in science and technology never stops. By the time a radar set is turned over for use, R & D men have already come out with the design of another equipment, better in performance, more compact, and so on and so forth. How much radar might ultimately be improved will be seen from what looks to us as an instructive example.

In the United States, scientists have compared the performance of the sound-locating apparatus of bats and the best radars. Radar designers take special inte-

rest in this study because the sound-locating apparatus of bats, weighing a fraction of a gram and occupying a space of about one cubic centimetre, can do the same job as a radar equipment with a weight of hundreds of kilograms and a size of hundreds of cubic decimetres.

The observations have shown that:

1. Bats can pick up signals comparable in strength with noise while for radars echo signals must be well above the noise level.

2. Bats measure range and angular positions of reflecting objects to a higher degree of accuracy than existing radars.

3. In hunting for mosquitos, bats fly in what is known as the "pure pursuit course" (sometimes aptly called the "hound-and-hare" course), an optimum flight path calculated for ground-to-air missiles and interceptor fighters by their computers. It appears, the built-in computers of bats do their jobs on a par with up-to-date man-made machines. The capabilities of bats' built-in computers will appear still more amazing if we add to this the fact that a bat can catch at least 175 mosquitos in a matter of 15 minutes, which works out to one mosquito in six seconds. Cases have been recorded when bats caught two mosquitos in one second. That is an enviable standard of performance for any search and fighter-control radars.

4. Bats live in caves and find their ways about with their locators. A great number of bats send out "exploring pings" at the same time, but they do not seem to interfere with each other. Apparently, bats do not respond to the pings used by other bats or to stray interference, a quality not possessed by present-day radars. Neighbouring radars can be a great nuisance to one another, and control of interference still remains a problem for radar specialists. In the military ap-

plications of radar the adversaries make it a point to jam each other's radars by sending out strong noise in their directions. The laboratory experiments on some bats have shown that a fairly strong ultrasonic noise had hardly any effect on the bats in using their natural locators. So far, radars have not been able to show an equal immunity to interference.

5. Estimates have shown that the signals generated by bats pack 0.11 watt per kilogram of a bat's weight and about 0.03 watt per cubic decimetre of a bat's volume. For a representative radar, the respective figures are 0.2 to 1.0 watt and 0.2 to 0.5 watt. This is the only characteristic in which man-made radars have outexcelled the bats.

That is poor consolation, though, because the "power plant" of a bat has to sustain its flight and the functioning of its internal organs, and only a small portion of the overall energy can be supplied to the bat's locator. In contrast, the power source of a radar is practically entirely used for location. So, our comparison has been a bit unfair, and even in this index of performance the nature-made locator still leads the man-made equipment.

6. In detecting and chasing a multitude of mosquitos, a bat has to process a wealth of information comparable with that handled by an airport surveillance radar. However, a bat manages to do that with an "equipment" weighing a fraction of a gram and a volume of a fraction of a cubic centimetre, while an airport surveillance radar set tips the scales at several hundred kilograms and occupies a space of several cubic metres.

American scientists of the Massachusetts Institute of Technology have investigated the signals that bats use in the various phases of their flight, namely during the initial stage, or search for a mosquito; the intermediate stage, or detection of a mosquito; and the final

stage, the pursuit and catch of the mosquito. They have found out that the ultrasonic signal strongly changes in frequency from phase to phase (or stage to stage). The wavelength of the signal, that is, the distance that a wave covers in travel during one cycle of oscillations, has been found to be 3.4 millimetres for bats and 30 millimetres for the radar used for comparison. What is important about the bat's wavelength, however, is the fact that within the same signal it can vary between 3.4 and 7 millimetres. In none of the man-made radars can this be done! It is not at all unlikely that the secret of the extremely high performance of bats' locator lies there.

One species of bats has an ear built like a selective reflector which can send out signals in different directions according to frequency. In fact, the animal generates a signal whose frequency varies within its limits. Recently, it has been proposed to build systems using this principle (that is, a swept-frequency signal and aerials with a selective radiation pattern) for direction finding.

Attempts have been made to turn out scaled-up replicas of bats' locators. In the United Kingdom miniature sound locators have been built for the blind. Sound is reflected from different objects differently, depending on their distance, shape and surface. After a brief instruction on the use of the locator, you would be able to tell a smooth from a rough surface. It operates on the principle of the nature-made locator built into bats.

One and the same locator enables bats to avoid collisions with large obstacles and to catch evasive insects. That is, the locator yields enough intelligence for a bat to tell stationary obstacles from moving "targets", although both classes of objects are in a constant motion relative to a bat.

One species of bats prey on small fish rather than on

insects. The bats spot the fish when they rise to the water surface or, rather, when their fins just appear above the water. Experimentors have noted that this species of bats can tell one target from another or recognize a target resembling a fish's fin. It appears bats know how to identify targets from their echoes, a problem of urgent interest to radar specialists.

To sum up, radar designers have got very much to do before they can come closely enough to the effectiveness of nature-made systems.

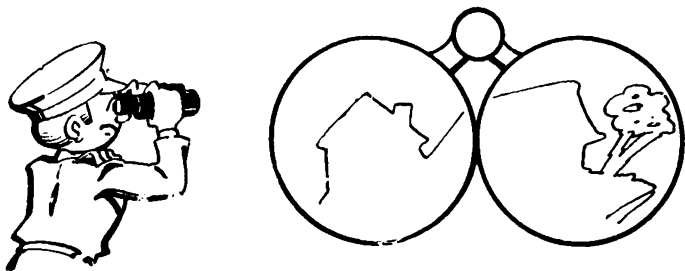
## TARGET'S WAY OF HIDING



We have already learned that radar does many jobs for the military. Above all, it can detect and identify targets in the air, on water, and land. On the basis of radar data, the military decide whether a given target constitutes a threat to a nation's security, and take appropriate measures if it does. In controlling the interceptors or guiding missiles, they use radar too.

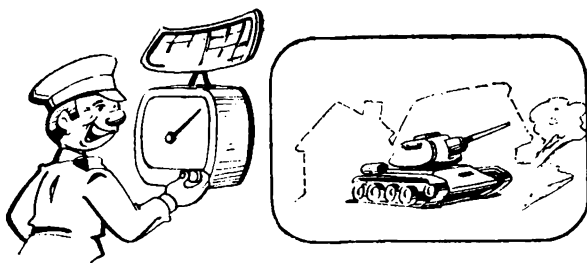
Naturally, the adversaries use what they can to prevent the other side from detecting and destroying this side's installations. Most often, this is done through the use of radar concealment or camouflage.

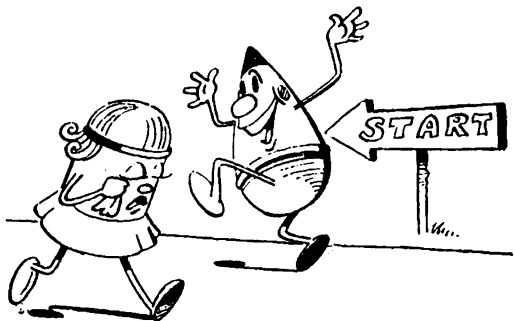
Man has used different ways of camouflage since very



long ago. A hunter stealing up to game in the woods tries to look as much like the trees as he can, so that it is hard for any animal to see him. Animals, too, show many ways of concealing themselves. Some can even change colour to match the surroundings.

Soldiers, too, use camouflage. The armed forces in all countries have widely been using uniforms painted some protective colour or camouflage nets over the materiel. Unfortunately, this sort of concealment is good only as far as optical observation is concerned, that is, one with the unaided eye, or with a pair of binoculars, or an optical range finder, and the like. No amount of war paint or a camouflage net with some tree branches put in here and there will hide a tank or an army truck





from a radar operator. Nor can ordinary camouflage hide an aircraft or a missile in flight. This is where special radar camouflage comes in.

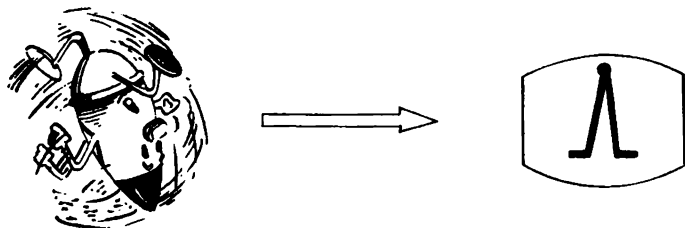
As an example, we shall take up radar camouflage for the warheads of ballistic missiles. The first step is usually to give the warhead a shape that will produce the faintest radar echo possible. According to studies, this should be one free from sudden changes in outline and from flat or cylindrical surfaces at right angles to the direction of observation. Best of all these requirements are satisfied by a narrow cone with its point facing the observer, while its base is given the shape of a sphere. Even though shaped like that, this type of warhead will not guarantee a faint echo if it is unstabilized, that is, allowed to tumble in flight. A tumbling warhead will present itself to an observer from all directions in some of which its echo may grow very strong. This is why the warheads of ballistic missiles are stabilized in flight and oriented along the flight path so that their echo is reduced by a factor of several hundred. In turn, this cuts down the distance at which the presence of a target can reliably be established by

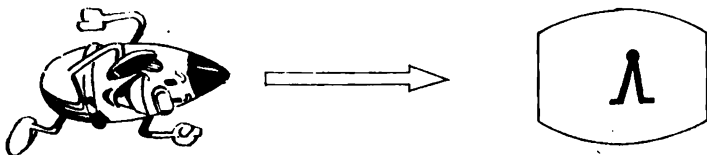
radars, and also the margin of time for the attacked side to alert its defences.

Another way of reducing an echo from a target is to give it a coat of some material that readily absorbs radio-frequency energy. Every country does a good deal of work on these radar paints. Some of these materials when applied as a coat six to twelve millimetres thick will reduce the echo by a factor of 20 to 1000. It looks as if a target dons a camouflage cloak which makes it hard to detect. Unfortunately, this cloak is still fairly heavy — one square metre of radar paint weighs five to six kilograms, and this drastically subtracts from the weight of the warhead. Besides, a particular radar paint effective on one frequency or a band of frequencies is usually ineffective on other frequencies. Yet, research and development on radar paint continues.

In radar, as in any other field of the military art, an unending competition is under way between the attacker and the defender. As the prospective attacker introduces a warhead that reflects a weaker echo, the prospective defender answers with a radar that can illuminate this warhead with a stronger signal or detect a weaker echo.

With some methods of radar camouflage, however, no increase in transmitted pulse strength will help. Examples of such methods are so-called chaff (or

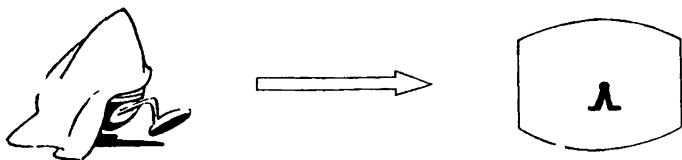




“windows”) and decoys. Chaff is a general name applied to radar-confusion reflectors. A decoy usually refers to a reflecting object used in radar deception and having the reflective characteristics of a true target. Released near a true warhead, these reflectors will produce a multitude of pips on radar scopes. It is difficult to tell which is which. Anyhow, much more time will be needed to do that, and this is what the attacker is after.

Why is it then that no increase in signal power is of help with chaff or decoys? The point is that an increase in the strength of the transmitted signal brings about a proportionate increase in the strength of the echoes from both true targets and decoys. This is another way of saying that the relative strength of interference remains the same.

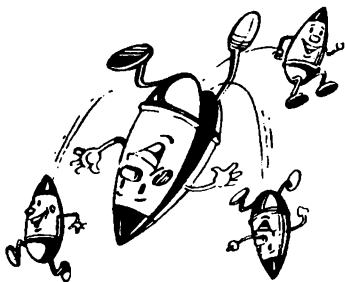
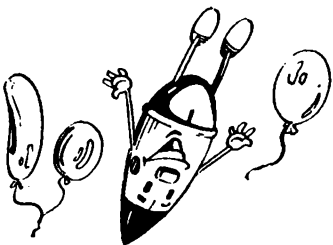
Different decoys are used on the various legs of the flight path of a missile. In the middle portion, where the missile travels outside the atmosphere and the air puts up practically no opposition, these are light-weight metal reflectors or metallized inflatable balloons. They are chosen for shape and size so that they will simulate



the reflective properties of the warhead best. Since in a vacuum all bodies, light or heavy, move in a similar manner, the operator will inevitably note several targets moving alike and producing echoes comparable in size.

On the final leg of the trajectory, when the warhead and the accompanying reflectors enter the denser atmosphere, the light-weight reflectors would lag behind and fail to mask the heavy warhead as effectively. A way out is to use heavy-weight decoys that would travel in the atmosphere at the same speed as the warhead. Unfortunately, the cost of putting a kilogram of mass in a flight path is the same, be it a warhead or a decoy.

It is apparently for such reasons that missile and radar experts believe heavy-



weight decoys are no cure of all ailments. Sometimes it will pay to use a warhead that will split up in several warheads each flying in a different direction. The defender will then find himself in the place of a hunter who is after two or more hares at a time.

By using suitably shaped warheads and giving them coats of radar paint, the attacker seeks to prevent their detection and to have the defender establish the very fact of an attack at the latest possible instant. When use is made of decoys or chaff, the situation is reversed, in a sense. The attacker no longer seeks to conceal his intentions. A composite target made up of several objects is usually much easier to detect than a single one. In fact, the defender learns about an attack at an earlier time. Unfortunately, he faces now a new, no less ticklish problem—that of deciding which target constitutes a real threat so that it can be destroyed in time, and of doing that during the few minutes that are usually left for taking a decision.

This problem can be coped with if the radar shows not more than five to ten target echoes. If there are more echoes, even a modern computer will fail, not to speak of a human operator, in identifying a true warhead in the host of twinkling spots. As a rule, each radar set is designed to handle a definite number of targets at a time. With a greater number, the set is overloaded, and some of the targets may be overlooked. This is precisely what the attacker is after in using decoys. The overlooked targets may well include a warhead which will sneak past the defence line undetected.

The effectiveness of present-day radars is to a great extent dependent on the speed and memory capacity of their computers which process the signals received, sort them out, and separate true targets from false ones. In expert opinion, any further progress in anti-missile

defence will depend on improvements in both radar equipment and the associated computers.

Among the other devices that the attacker may use in order to reduce the effectiveness of the defender's radars may be vehicles carrying jammers, that is, electronic devices for intentionally introducing unwanted signals into radar sets. With enemy jamming, a friendly radar may completely fail in detecting any approaching target. This is why the frequency used by a radar is a strongly guarded secret. Of course, the adversaries do whatever they can to identify each other's operating frequencies, at least, approximately.

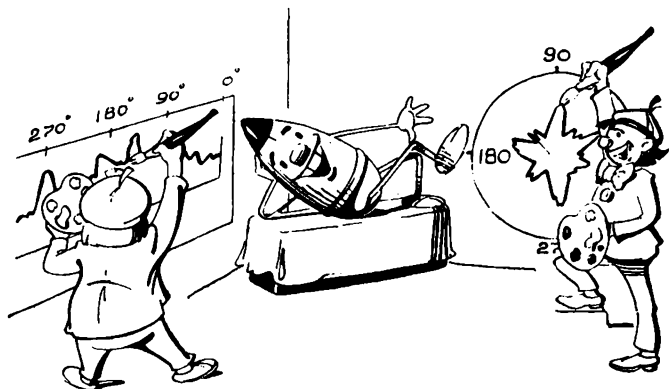
We have discussed only some of the methods of radar camouflage applied to missiles. There are a host of others, but no single book can cover them all.

## HOW TARGETS ARE IDENTIFIED

From the story about radar camouflage (which the author has done his best to make convincing) the reader might think there is no use watching targets with the aid of a radar set. For, the reader may reason, one has no way of identifying a target even though one may have been lucky enough to tell it from interference, noise, chaff, or decoys.

After he has turned the reader a pessimist, the author undertakes to prove that the situation is not that hopeless, after all. For radars do work and identify targets. So our story will be about how radar identifies the targets it has detected.

How can you identify a person you meet if you have not seen him before? You will surely do that if you have got the person's photograph or, at least, a verbal description like the one used by criminal investigators to list the basic features of the wanted man: the shape of



his nose, the shape and colour of his eyes, the shape of his face, etc.

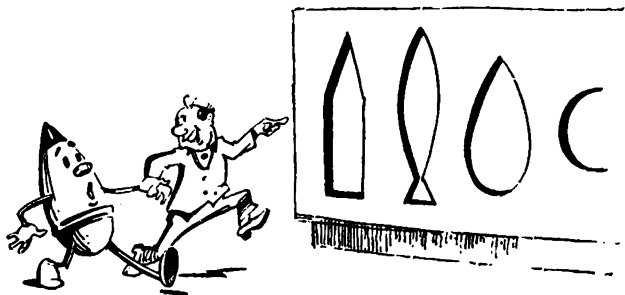
Radar targets may, too, be identified in a similar way. True, what is used for the purpose is neither a painting nor a photograph. The purpose is served by a specific radar picture produced as follows. The target of interest is taken to a radar range, mounted on a support, and turned in all directions. In each position, the target is illuminated by a radar beam, and its echoes are recorded. We already know that the strength of an echo depends on the angle at which the radar beam is reflected. For some angles the echo is strong; for others it is weak. The echo is at its weakest when the target faces the radar with its pointed tip, and is at its strongest when the target is positioned sideways to the beam.

With the angle of the target plotted along the  $x$ -axis of a Cartesian coordinate system and with the echo strength along the  $y$ -axis, we shall obtain a back-scattering pattern of the target — a quiet curve with peaks, valleys, and narrow gaps. As an alternative, we may

plot it in a circular or a polar system of coordinates. Then the angle of the target can be plotted along the arc of a circle, and the strength of the echo as a distance on the respective radius. The result will be a back-scattering circle diagram having the shape of a closed curve. It will show the same sequence of peaks, valleys and narrow gaps as the Cartesian diagram. This circle diagram looks like a flower. With a plain target, this flower will have three or four petals (or lobes, in radar parlance) and will look like a poppy. With composite targets, such as artificial satellites or aircraft having a multitude of projecting parts and sharp edges or angles, the diagram will look more like a daisy.

Now we have got a radar portrait of our target. Other targets may have their portraits drawn in much the same manner. If a target happens to be bulky and cannot be taken to a radar range intact, a scaled-down model will do, provided the illuminating radar uses a wavelength scaled down in the same proportion. The resultant portrait will then be exactly such as if we had watched the actual target.

Now we may collect all the portraits in an album and give it the title, "Album of Targets for (such-and-such) Radar Station Operating at Frequency  $F_0$ ". Why "such-and-such"? Can't we use the same album for another radar? Unfortunately, not. Let's change the carrier frequency of the transmitter pulse and see what will happen. With a plain target, a small change in the carrier frequency will leave the radar portrait practically the same as it was before. The back-scattering pattern will have about the same number of peaks, although their amplitude and relative position may be slightly different. With a composite target, even a minute change in the carrier frequency will bring about drastic changes in the back-scattering pattern. Everything will be different — number of peaks, their rela-



tive positions, and their magnitudes. So there must be a separate album for each carrier frequency.

To get an idea about how radar men use the back-scattering patterns of targets, we shall discuss two cases.

Let the target be unstabilized, that is, tumbling at a rate of, say, 10 revolutions every minute. That is, every minute we can obtain a chain of ten complete radar portraits of the target recorded on tape. We pick the best one and check it against the album.

The portrait in the album precisely checking with the target will unerringly identify it. However, this happens not always. Or rather, this does not happen almost always. Most often, the actual portrait differs in detail from the closest standard in the album. It may have, say, the same general outline but there may be more peaks. These peaks may show on another standard pattern, but in the standard the main peak may be seen shifted left. Specialist books describe several criteria for the identification of standard and actual patterns, but they all allow for an amount of uncertainty. That is, in choosing the best semblance we may still commit an error. In the worst case, the same actual pattern may look like two standards at the same time. The best you can say then is that the actual target looks

like standards Nos. 14 and 27, but you cannot identify the object detected. Experts in the theory of probability say the only way to make a choice is to toss a coin or throw dice. These unbiased umpires will decide which target has actually been observed. What if they happen to be in error? Well, nothing can be done then.

Why is it that the same actual target looks like two standards at the same time? If we leave out troubles in the radar equipment, two main causes will remain. One is noise, already familiar to us. It may add two more peaks to or clip one off the back-scattering pattern. We already know how noise can be controlled. The other cause is this. The target may follow a flight path such that the radar will see it at a slightly different angle than it has seen the standard. This is nearly the same as an attempt to identify a person seen half-faced from a photograph taken full face. In expert opinion, only computer can cope with this problem, provided it knows how the target tumbles and its shape. Then we can sometimes obtain a portrait of the target in the desired plane and identify it.

It is a far harder job to identify a stabilized (nontumbling) target. Suppose you are in a motor-car-show room. Perched up on turntables are new cars, all shine and lustre. As a turntable makes a complete revolution, you can see the car from all sides without stepping an inch. That is an analog of a tumbling target. Now picture yourself standing on the shoulder of a highway and watching the cars passing by. You can only see the front of an approaching car, the back of a receding car, and its side when it is just opposite you. That is an analog of a stabilized target.

Before it can draw a portrait of such a target, a radar station should watch it for a long time. Nevertheless, the portrait may lack some important detail, and the identification may prove a hard problem. In fact, the

actual pattern may look like several standard patterns at a time — the greater the uncertainty, the greater the risk of an error. In such cases, one may use intelligence obtained "on the side". As one technical journal has suggested, the final choice in the case of a target looking like several standards may be made on the basis of the flight path — targets having a different trajectory may be discarded at once. There are also other ancillary methods. Despite all devices, however, stabilized targets can be identified with less reliability than the tumbling ones. This is one more reason why it is sought to stabilize warheads or satellites.

It may so happen that the target whose portrait a radar station has drawn looks like nothing in the album. This will be an indication that a new type of target not yet recorded in the album has appeared. Now it may be entered there on a tentative basis. The next time we shall be able to recognize it as a familiar stranger. It will remain a stranger all the same, because we know practically nothing about it. But even a bare record of its flight path may turn up as a big help in some situations. For nobody will hurdle anything in outer space just for fun — that would be too expensive.

That is how, in general outline, radar men identify targets from their radar portraits. Of course, ours has been a scanty story because in a popular book you cannot possibly describe all the details. As to the main ideas, they have been taken up.

## WE'VE LEARNED ONLY PART OF THE STORY

This is the closing chapter of the book. It's time to say good-by to you. The author takes a good measure of comfort in that the reader will surely meet radar again. That hardly need be proved. There is a plenty of books on radar, both specialist and popular, and

some will certainly find their ways into the hands of an eager reader.

There is a reason for the author to feel a bit sad. Any popular-science book dealing with specific advances in science and technology grows obsolete almost at once. What has been described in it as "unique" or "amazing" may appear hopelessly old in a few years from now. Radar engineering which develops in big strides leaves no doubt about that. There is some hope, though, that the radars of the future, however more sophisticated they may be, will still use the same underlying principles, the same signal detection techniques, and the same functional algorithms. Then this book will still be of use to the reader of that time.

A few words are in order about those to whom this has been the first book on radar. Don't be under the delusion that you have learned everything there is about radar. Just underscore in red the places where the author has had to end up with the vague "other methods exist. . .", or "other approaches to the problem are known", or something like that, and you will see how many gaps there are in your knowledge yet. At best, the book is only an elementary outline of radar, a fleeting acquaintance with the problems radar men have to deal with. Each one is the subject of profound scientific research and of heated debates in special journals and at conferences.

As far as the author can recall, there has been no limitation imposed on the use of tables in this book. Taking advantage of this omission, we shall include one and the last table. On its left are some divisions of radar theory; on its right are some of the basic disciplines whose knowledge is essential to each division.

On top of all, a present-day radar specialist must know how to program and run a computer, work painstakingly, and have a sense of humour.

So think twice before you rush to the personnel department of a radar establishment if you know only what you have learned from this book. It would be sheer waste of time to take up radar without proper groundwork. Get down to brass tacks and do not be afraid of the table — you will have to know no less in any field of science or technology.

One more thing before you close the book. I have almost never met radar men who have been disillusioned in radar. So, till we meet again, dear reader.

*Table One and Last*

Signal waveform selection	Mathematical analysis, theory of functions, theory of functions of a complex variable, mathematical logic, probability theory, information theory, code theory, radio circuit theory, etc.
Evaluation of radar performance	Theory of radio wave propagation, physics of the ionosphere, probability theory, electrodynamics, information theory, matrix theory, statistical radio physics, etc.
Aerials	Aerial synthesis, field theory, radio wave propagation, electrodynamics, mechanics, solid-state physics, strength of materials, etc.
Signal detection and data processing	Statistical radio engineering, statistical radio physics, probability theory, information theory, statistical theory of hypothesis testing, pattern recognition theory, optics, infrared techniques, television, etc.

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To-day, radar in one form or another is likely to turn up everywhere: in the street, at the waterfront, in an underground motor-road. By far the widest use of radar is made by the military and scientists. In all of these fields thousands upon thousands of radar sets are at work. Some of them are small enough to be fitted into spectacles, others weigh hundreds of tons.

In this booklet based mostly on Soviet and foreign periodicals the reader will find a story of radar. It tells, in a simple and informal manner, what radar is, what it does, and how, and why is it that radar has come to play a leading role in the present-day world. The booklet uses not a single mathematical formula; where necessary, pictures come to the reader's help.

The booklet has been written for a layman interested to know how and where radio and electronics serve man. From it, the reader will learn quite a number of facts, sometimes unexpected, about the capabilities of radar.